DEVELOPMENT AND ECONOMIC APPRAISAL OF A LIGHTWEIGHT ZEOLITE CEMENT BLEND FOR HIGH TEMPERATURE – HIGH PRESSURE OIL AND GEOTHERMAL WELLS

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A

PROJECT

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

By

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Fairbanks, Alaska

December 2015

Abstract

With ever-increasing global energy demand, it is of vital importance that technology consistently meets industry requirements. As high temperature-high pressure reservoirs become more and more profitable, the energy industry can be expected to exploit them. Hence, a versatile cement system that can be used in such reservoirs would need to be capable of ensuring well integrity under such conditions. However, in order to overcome most of these challenges, cement systems are often too dense to pump into a formation without damaging it. Therefore, a lightweight cement is needed. One promising means of delivering a lightweight cement that meets these rigorous demands is to replace a portion of the API cement with a natural pozzolan such as a zeolite. The zeolite cement blend developed in this project has a density of 13.5 ppg, far lower than the 17 to 18 ppg cements that would otherwise be used.

Through a trial and error process of replacing portions of API class H or G cement with six different zeolites, an acceptable zeolite cement blend was found, along with the necessary system of additives to ensure that it performed within existing specifications for oil well cements. Each of the cement blends was subjected to high temperature-high pressure testing of consistency behavior, fluid loss, and compressive strength, along with studies of modification with carbonation.

This study also endeavored to show that such a cement system was economically viable. This was done using a number of case studies including both oil and geothermal wells. The cement costs of the cement were found by studying each component. The associated costs

associated with the cement were subjected to a Monte Carlo simulation to reflect better the variability expected in a well job. By adding the two, and comparing the cost with a similar job carried out with a standard class H cement, the economic viability of the cement was established. In addition, the cost per kilowatt-hour and projected revenues for the geothermal projects were calculated to show that it made financial sense to use the zeolite cement blend.

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Acknowledgements

I would like to take this opportunity to thank the members of my Graduate Advisory Committee Dr. Santanu Khataniar, Dr. Abhijit Dandekar and Dr. Shirish Patil for their guidance and immense patience over the course of the research. I would also like to thank Dr. Matt Bray and Justin Cannon for instructing me in various experimental procedures. Furthermore, I would like to thank the University of Alaska at Fairbanks (UAF) itself for fulfilling its vital role in the successful completion of this research. Last but not in any way the least, I would like to thank my family and friends who supported me and raised my spirits throughout my time as a graduate student at UAF.

1. Introduction

The demand for energy is an ever-present constant in the modern world. While there are a wide variety of sources from which energy can be harnessed, chemical fuels like petroleum remain the most efficient, not to mention versatile in their applications. The demand for energy in the world has been increasing steadily for many decades. Factors such as increasing global population and high growth rate emerging economies mean that this trend of increasing energy demand can be expected to continue for many years to come. In order to address this growing need, it thus becomes necessary to produce increasing amounts of oil and gas. To do so, it is vital to drill more wells and set up the necessary supporting infrastructure to convert unrefined crude into a marketable product.

Hence, it would make sense to research better techniques and products related to drilling a well quickly, cheaply, and safely. One such component is the cement used. Cementing is vital to a well as it isolates pressure regimes and ensures well stability. With increasing focus on offshore development, especially in ultra-deep water regions, new wells commonly encounter high-temperature high-pressure (HTHP) systems.

Geothermal energy would also benefit greatly from the development of well engineering. Geothermal energy is an abundant resource, albeit a challenging one to produce from compared to other sources of energy. In a geothermal system, hot formation water is produced from the well. This heat energy of the Earth is then utilized to drive a turbine that is connected to a generator, thereby producing electrical power. All of the heat energy in the Earth down to a depth of 10 kilometers is 1.3×10^{27} Joules, which is the amount of heat

energy contained in $3.0x10^{17}$ barrels of crude oil (Lund, 2007). To put this in perspective, at the end of 2009, according to BP's Statistical Review of World Energy 2010, there were $13.33x10^{11}$ barrels of proven oil reserves on the planet. Also according to BP, in 2009, the world used 11164.3 million tons of oil equivalent for primary energy consumption. This corresponds to about 80 billion boe (barrels of oil equivalent) per year. This means that the heat contained within the Earth down to a 10 kilometer depth could meet today's primary energy consumption rate for 3.75 million years. Of course, this cannot all be tapped; however, gaining access to even a modest portion would represent a tremendous amount of electricity-generating potential.

Furthermore, the potential for Enhanced Geothermal Systems (EGS) is enormous. However, there are many obstacles to overcome. Chief among these are the challenges faced in drilling and completing injection and production wells that are robust enough to last appreciable amounts of time in the hostile high-temperature, high-pressure (HTHP) environments that are typical of deep geothermal formations. EGS wells will have to be even greater than 5000 m (over 16400 ft) deep (Falcone & Teodoriu, 9th - 12th June, 2008). At this depth in geothermal formations, wellbores are exposed to high pressures, high temperatures, and corrosive fluids (usually due to the presence of heavy metals), all of which add up to a very hostile environment. Geothermal well failure most often begins with the casing cement sheath as "geothermal wells represent the most severe conditions for cements used in drilling" (Gaurina-Medimurec et al., 1994).

Thus, it is of primary importance that the wellbore cement be of the utmost robustness in both compressive strength and corrosion resistance. To protect the casing adequately, a sufficient quantity of cement needs to be pumped in order to ensure cement rise behind the casing. However, such HTHP formations can be easily fractured if too much pressure is applied downhole by the cement fluid column. Therefore, it is imperative that a lightweight cement provide the necessary well integrity without extensive cement losses into the formation and resulting formation damage.

To reduce the weight of the cement, a certain portion of the cement is replaced by a natural pozzolan, in this case, a zeolite that is lighter than the standard API cement blend. This reduces the overall density of the cement. To ensure the safety of the well, certain specifications (American Petroleum Institute (API), 2010) need to be met. These specifications for High Temperature-High Pressure (HTHP) cement are:

- A 24-hour compressive strength of at least 500 psi.
- Thickening time of at least 5 hours to reach 70Bc (Bearden units) to provide sufficient pumping time for the cement to required depths.
- Low permeability in order to provide zonal isolation, preferably less than 1 mD.
- Low free water to prevent cement shrinkage, preferably none at all, as dewatering also causes strength retrogression.
- Viscometer reading of less than 200 at 300 rpm.

In order to remain economically competitive, oil and geothermal wells have to be properly cemented to ensure integrity over the life of the well. As an example, geothermal wells in

Nevada have a failure probability of 20% (Lund, 2007). When an extremely deep well fails, remedial drilling and cementing of the well can almost double the cost of the project, increasing the cost of the energy produced. The current cementing system for HTHP wells requires highly specialized equipment, slurries with a cocktail of additives, and meticulous planning, with unpredictable results. Hence, it was deemed necessary to develop a highly reliable novel lightweight cement that could use the same equipment as standard oil well cements while containing fewer additives. This cement would need to have consistently reproducible properties meeting the API standards for oil well cementing in HTHP formations.

1.1 Objectives

1. Through a process of trial and error, develop a zeolite cement blend and an accompanying system of additives that can perform at the American Petroleum Institute (API) specifications for HTHP oil well cements.
2. Ascertain the cost of using the developed zeolite cement blend by calculating the cement and associated costs associated with it. Also, carry out a sensitivity analysis by constructing tornado plots.
3. Study the economic viability of a project using the developed zeolite cement blend (particularly a geothermal energy project) using case studies to calculate the expected revenue and cost per kilowatt-hour.

2. Literature Review

The cost of well cementing is in no way the most expensive task in well construction. However, cementing problems leading to well failure result in expenditures greater than the cost of the cement itself, since the entire well needs to be remediated. Despite its being a relatively minor cost in the bigger picture, it is important to have a proper cementing plan with a robust cement mix throughout the life of the well, all the way from inception to abandonment.

2.1 Well Cements and Additives

The different commonly available oil well cements are classified by the petroleum industry in accordance with the American Petroleum Institute (API) classifications published in API Specification 10A (24th edition, 2010).

- **Class A:** This is based on American Society for Testing and Materials (ASTM) Specification C150, Type I and is basically ordinary Portland Cement. This type of cement is primarily used when no special properties are required to complete the cementing job.
- **Class B:** This is based on American Society for Testing and Materials (ASTM) Specification C150, Type II. This is similar to class A cement but is available in High Sulfate Resistance (HSR) and Medium Sulfate Resistance (MSR) grades. This is particularly useful when producing sour crude oil from the well.
- **Class C:** This is based on American Society for Testing and Materials (ASTM) Specification C150, Type III and is characterized by early strength development.

The quickly increasing consistency makes this type of cement hard to pump. Class C cement is available in three different grades, namely, ordinary, High Sulfate Resistance (HSR), and Medium Sulfate Resistance (MSR).

- **Classes G and H:** These are the most widely used classes of cement for oil well cementing. They are basically ordinary Portland cement with calcium sulfate and/or water intergrounded or blended into the clinkers during the manufacturing of the cement. Both these classes of oil well cements are available in HSR and MSR grades.

It is important to note that in many cases, the unique requirements of the cement job cannot be fulfilled easily by a single class of cement. In such a situation, the properties of the cement being used must be modified to fit the job requirements. To achieve this, a system of additives must be used. The various types of additives and their respective functions are as follows (Petrowiki, n.d.):

- **Weight Reducing Additives:** In formations where the pore pressure is close to the fracture pressure of the formation, the weight of the cement column can lead to formation damage. In such cases, the weight of the cement is reduced by replacing some of the cement with a weight-reducing additive or by foaming the cement with an inert gas like nitrogen to reduce the overall density of the mixture. These additives are also known as lightweight extenders and are also used to combat lost circulation or to provide the cementing job with better fill-up and cement rise behind the casing. Some common examples are bentonite, attapulgite, gilsonite,

diatomaceous earth (DE), perlite, ground rubber, fly ash, microsilica, pozzolans and microspheres (glass spheres).

- **Strength Retrogression Additives:** Under extreme conditions of heat, especially in the presence of high pressures, cement tends to undergo a process of strength retrogression. In this, the cement strength degrades over time and may reach a condition when the well is no longer stable and is likely to fail. This is because the hydrated cement undergoes a slow phase transition above 230°F in which the calcium silicate hydrate (CSH) phase reacts with calcium hydroxide and is transformed into crystalline dicalcium silicate hydrate (α-C_2SH), which is much weaker (Imerys Oilfield Solutions, 2015). To avoid this, finely ground silica is added to the cement mix. The silica must be finely ground to avoid too great an increase in the viscosity of cement slurry. This silica is usually in the form of diatomaceous earth (DE) or microsilica.
- **Fluid Loss Additives:** Dewatering of a cement can cause a large drop in its compressive strength, which can cause well integrity to be lost. Therefore, fluid loss additives must be added to prevent this problem. These additives are also known as filtration-control additives. Some examples are synthetic polymers, cellulose, cellophane flakes, gypsum cement, diesel oil, nylon fibers, thixotropic additives, and latex and vinyl based polymers.
- **Retarders:** These additives are used to decrease the slurry viscosity and increase the setting time of the cement to provide more time for the proper placement of the

cement in the well. Some examples of retarders which achieve increased pumping times and better flow properties are lignosulfonates and organic acids.

- **Accelerators:** These additives are used to decrease the Waiting No Cement (WOC) time of the cementing job by accelerating the early strength gain of the cement through hydration. Some examples of this type of additive are gypsum, sodium silicate, sodium chloride, calcium chloride, potassium chloride, alkali hydroxides, seawater, and dispersants.
- **Dispersants:** These additives help increase the density of slurries for plugging while also reducing the hydraulic power required. The most commonly used examples of dispersants are sulfonated naphthalene formaldehyde and sulfonated acetone formaldehyde condensates.
- **Heavy Weight Additives:** These additives are useful in overcoming high pressures by increasing the slurry density. Some common examples of this type of additives are hematite, limonite, and barite.
- **Salt:** When the well is being constructed through a formation such as a salt dome or a formation with large amounts of shale or loosely consolidated sands, cement bonding with the formation becomes an important issue. In such a case, salt (sodium chloride) can sometimes be used as an additive to the cement to improve its bonding.
- **Thixotropic Additives:** These additives are used when it is desirable to achieve fast setting and/or gelation of the cement and reduce the lost circulation. This also

helps prevent gas migration by providing better zonal isolation from an early time after the pumping of the cement.

- **Radioactive Tracers:** These additives are used to trace flow patterns and detect leaks. Some examples are radioactive iodine ($_{53}I^{131}$) and iridium ($_{77}Ir^{192}$).

2.2 Zeolites

Zeolites are microporous, hydrated aluminosilicate minerals of the alkaline and alkaline-earth metals. About 40 natural zeolites have been identified during the past 250 years (Patel, 2012), some common ones being analcime, chabazite, clinoptilolite, erionite, ferrierite, heulandite, laumontite, mordenite, and phillipsite. More than 150 zeolites have been synthesized, the most common ones being zeolites A, X, Y, and ZMS-5. Natural and synthetic zeolites are used commercially because of their unique adsorption, ion exchange, molecular sieve, and catalytic properties. Major use categories for zeolites include catalysts, detergents, molecular sieves, and protective coatings for disposal of civil radioactive material. Despite all these uses, zeolites remain widely underutilized minerals.

Zeolite Formation

Prehistoric volcanic ash settled on remnants of inland seas that were essentially highly saline lakes. Due to its alkaline nature, the vitric volcanic ash metamorphosed into the crystallized minerals that we now refer to as zeolites. Due to highly heterogeneous depositional environments globally, each natural zeolite of a particular geographic location is unique in its chemical composition and arrangement of its crystalline structure.

Zeolite Structure and Properties

Zeolites are crystalline minerals with a framework structure of linked tetrahedra, each consisting of oxygen atoms surrounding a cation (positive ion—an ion is an atom that has lost or has gained one or more electrons). The framework contains open cavities that form channels and cages. It is the existence of these cavities, and what is contained within them, that give zeolites their unique qualities. The cavities are so voluminous that some zeolites can absorb up to 100% of their own weight in water (United States of America (U.S.A) Patent No. 6964302, 2005). Inside the cavities are alkali metal or alkaline earth metal cations. The alkali metals are those elements making up the first column of the Periodic Table, excluding hydrogen. They include lithium (Li), sodium (Na), and potassium (K), among others. The alkaline earth metals are those elements found in the second column of the Periodic Table. Among these are beryllium (Be), magnesium (Mg), and calcium (Ca). Along with the water within the pores, cations such as potassium (K^{1+}) or aluminum (Al^{3+}) are often to be found in the "parent" zeolite. The aforementioned water molecules can be removed from the zeolite by heating it with fire or an oven. The cations from the water within the pores remain and are only removed in ion exchange reactions when the zeolite is exposed to certain other ions. This ion exchange ability is one of the primary properties distinguishing zeolites from other mineral groups.

Why Zeolite Blended Cements?

Zeolites are porous and hydrophilic in nature and exhibit cement-like properties when mixed with water and calcium hydroxide. Furthermore, zeolites have a large surface area that gives them a high reactivity to the attack of OH^- ions during the hydration of the

cement (Uzal et al., 2010). Not only do zeolites have a significant silica content that would help resist strength retrogression in the cement, they are also lighter than conventional cement blends, thereby allowing the preparation of lightweight cement slurries. Therefore, zeolites are an ideal choice as a cement replacement material in the development of a novel cement blend.

Zeolite Availability

Zeolites are found in over 40 countries and produced commercially by many. China is the main producer, with a production capacity of 2,000,000 tons (in 2011), followed by the Republic of Korea at a production capacity of 240,000 tons and Japan at 155,000 tons (Virta, USGS Minerals Statistics and Information, 2012b). Other major producers of natural zeolites are Turkey, Jordan, and Slovakia. The U.S. is a major producer as well, producing 62,000 tons in 2011 (Virta, USGS Minerals Statistics and Information, 2012b). An estimate of worldwide reserves is not known, but generally is considered large.

The U.S. has several hundred known deposits in many states. The states with commercially viable deposits (meaning they are of sufficient size and purity to be mined commercially) include Alabama, Alaska, Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, South Dakota, Texas, Utah, and Wyoming (Jana, 2007). Zeolite deposits that are too small to be considered commercially important are also found in many western and Midwestern states. The area of the U.S. that has significant deposits as well as current operational zeolite mines is the Basin and Range Province in the western part of the country. This is a vast section of land that is bordered on the west by the Sierra Nevada

Mountains and on the east by the Rockies. It runs from its northern end in southern Oregon and Idaho to its southern end across the Mexican border; its southeast corner includes part of Texas as well. Many deposits in the Basin and Range Province are sizeable and of high purity.

Zeolites are found in beds at shallow depths or exposed on the surface. The beds can range in thickness from a few centimeters to many meters and can run laterally for much farther. For example, the Bowie chabazite formation in Arizona has a bed that is only half a foot thick but still has a great lateral expanse (Eyde & Irvin, 1974). Because of their shallow depths, mining for them is relatively straightforward, consisting of standard surface mining techniques.

Of all the natural zeolites, there are only 6 that are commonly found in large, mineable beds. These are analcime, chabazite, clinoptilolite, erionite, mordenite; phillipsite–ferrierite also exists in large deposits, but these are fewer in comparison (Sherman, 1999). According to the 2011 USGS Minerals Yearbook, prices in 2011 for milled zeolite granules and powder were $40-$800 per metric ton. The average price of clinoptilolite, the most plentiful natural zeolite, was $160 per ton, whereas high grade, activated chabazite had a significantly higher cost at around $10 per kilogram ($10,000 per metric ton) (Virta, USGS Minerals Statistics and Information, 2012a). It should be noted that the costs of zeolites depend upon purity, milling size, and scarcity. The high cost of chabazite, for example, is due to the fact that the Bowie, Arizona deposit is the only known deposit of its size and purity in the world (GSA Resources, n.d.).

Zeolite Cement Research

Zeolite-containing cement research and development was initially carried out by Halliburton Energy Services beginning in the late 1990s. The aim was to develop a wellbore cement lightweight enough to be used in weak formations without causing damage and also flexible enough to allow the changing of cement slurry densities on the fly by altering only the water ratio. Halliburton developed various zeolite-containing cements that were protected as intellectual property by the issuance of a series of five patents.

In early 2005, Halliburton introduced its first and only commercialization of the technology as VariSeal™ in Canada. The primary attributes of VariSeal™ were:

- Allow for density adjustments within a single blend.
- Eliminate the need for separate blends for lead and tail slurries.
- Extend water-absorption without retaining free water.
- Reduce placement Equivalent Circulating Densities.

Halliburton continues to market VariSeal™ in Canada in five specific blends, plus VariSeal™1500 Thermal which is described in Halliburton sales brochures as resistant to strength retrogression at temperatures of 110°C. VariSeal™ 1500 Thermal is marketed as lightweight cement for use in heavy oil applications. Halliburton does not market VariSeal™ or VariSeal™1500 in the U.S. In July 2008, Halliburton licensed the technology embodied in the five zeolite-containing cement patents, along with foreign

equivalents, to Trabits Group, LLC. The issued license is worldwide and includes oilfield, geothermal, and water wells as Fields of Use.

Further development of a zeolite-containing lightweight HTHP cement will provide operators with an easy to use, flexible cementing system that saves time and simplifies logistics. The requirement to sterilize pumping equipment before use, as with CaP cement (i.e. Calcium – Phosphate Cement), is eliminated. This is because zeolite cement itself is a Portland cement that is handled normally by conventional cementing equipment. Furthermore, as Portland cement is not in any way exotic or difficult to obtain, base materials for it will be commonly available. Simplifying things further, zeolite cement will not require air or nitrogen foaming for density reduction to achieve lightweight qualities, thus lowering cost and the risk of increased cement permeability. Density reduction will be done by adding extra water to the cement slurry. Another advantage this provides is the elimination of creating complex lead and tail slurries of differing densities. In addition, the sensitivity and incompatibility issues in the selections of retarders and accelerators are minimized or completely eliminated, as zeolite cements are expected to be compatible with normal cement additives.

2.3 Zeolite Blended Cement Development Tests in Atmospheric Conditions

According to a report by Patel (Patel, 2012), six different zeolites were tested. Each zeolite tested primarily had two different sizes that were part of the testing, namely 5 microns and 44 microns. 10 micron size zeolite particles were also tested in some cases. However, since

their results were relatively poor, they were not tested as extensively as the other two particle sizes.

The six zeolites were:

- Analcime
- Ferrierite (Ferr)
- Mudhill Clinoptilolite (Mudhill)
- New Mexico Mine #1 Clinoptilolite (NM1)
- New Mexico Mine #2 Clinoptilolite (NM2)
- Chabazite.

XRD analysis determined that the analcime samples were defective, so further testing was conducted using only the five remaining zeolite samples. In each case, a portion of cement was replaced with one of the zeolite samples and the resulting cement slurry was subjected to atmospheric consistency, free water, and compressive strength testing.

Atmospheric Consistency Testing

In Patel's report (Patel, 2012), the atmospheric consistency test uses the Chandler Engineering Model 1200 Atmospheric Consistometer, as shown in figure 2.1, to determine if a slurry will remain pumpable after 5 hours. A slurry is deemed pumpable if it produces a reading of 75Bc or less on the potentiometer that is included on the lid of the brass. The procedure for this test is run for 5 hours or until the potentiometer reads greater than or equal to 75Bc.

Figure 2.1: Chandler Engineering Model 1200 Atmospheric Consistometer

Free Water Test

Dhaval Patel's report states that the goal of the free water test is to measure the amount of water that bleeds from the cement slurry over the course of 2 hours. In order to minimize any cement shrinkage due to settling of the solids, the amount of free water should be as small as possible. The maximum amount allowable per API Specification 10A is 5.90%. However, for this study (Patel, 2012), a maximum threshold for free water was set at 2% by volume. This will help maintain well integrity by reducing chances of cement failure under tension.

Compressive Strength Testing

The compressive strength of cement samples was determined using TerraTek equipment that crushes the sample while collecting force and displacement data (Patel, 2012). In addition, further data regarding the density of the sample was collected. By measuring the mass of the sample before crushing, the initial density could be calculated by measuring the dimensions of the sample. After crushing, the mass could be measured again, but to get data that was more representative, the crushed sample was soaked in water and its volume measured by buoyancy forces. The mass of the soaked sample was then taken to calculate the density of pre- and post-soaked samples. The porosity of the cement, which should be as low as possible, can also be calculated from these measurements.

2.4 Primary Testing Discussion

Since the objective was to form a lightweight cement slurry at the highest possible compressive strength, this phase of testing sought to answer the following questions:

- What particle size of zeolite should be used?
- How much of the cement should be replaced with the zeolite?
- What are the effects of the curing temperature on the cement slurry?
- What system of additives should be used?
- Which zeolite shows the greatest promise of being technically and economically viable?

The free water test and the atmospheric consistency tests are used to completely exclude any cement slurry mixture that does not meet its specifications (Patel, 2012). This is because any cement blend not capable of being pumped is of no use to us. In addition, any cement blend that gets easily dewatered fails to meet the minimum standards. Therefore, it is the compressive strength testing data that will allow us to compare the various zeolites and their respective particle sizes with one another.

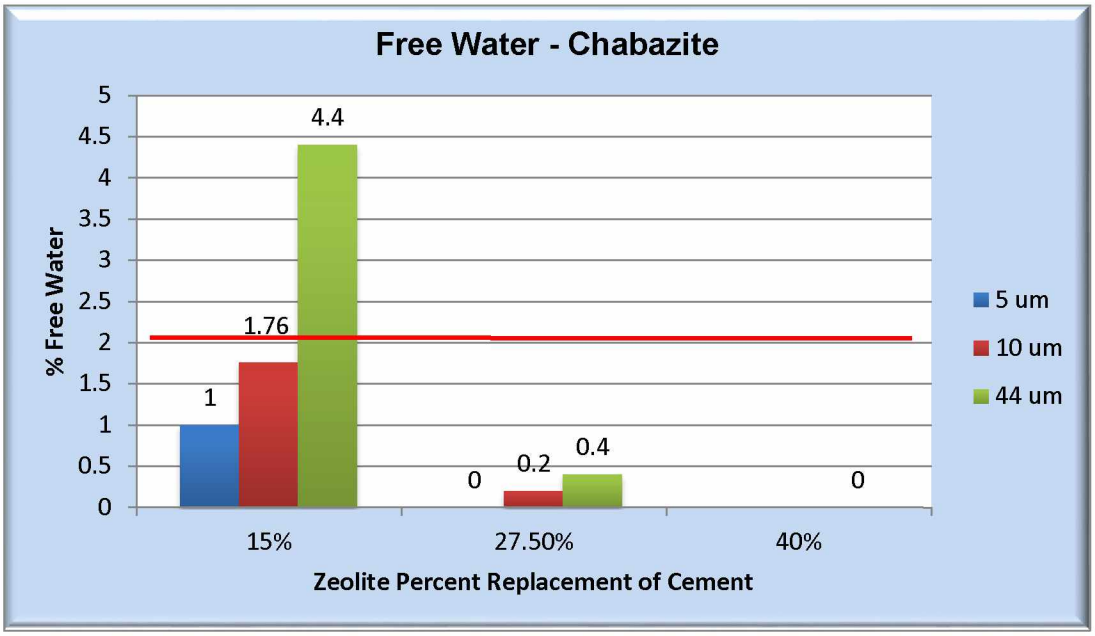

Figure 2.2: Chabazite Free Water Plot (Patel, 2012)

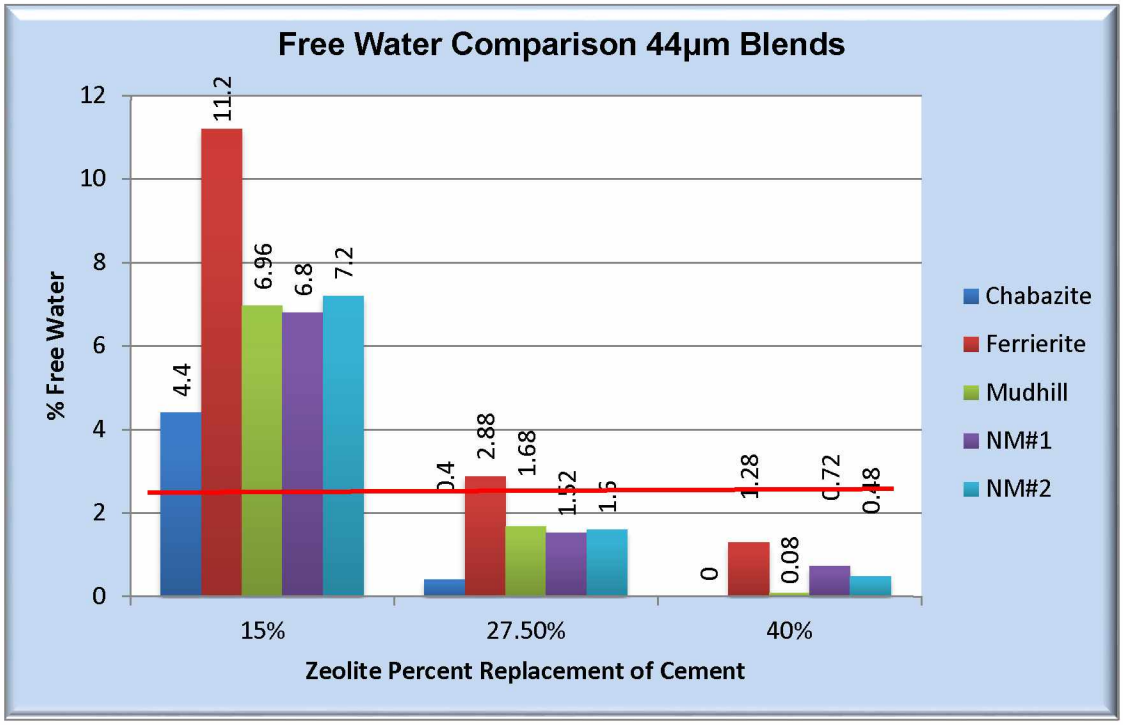

Figure 2.3: Comparative Free Water Plot for 44 micron Zeolite Cement (Patel, 2012)

The free water test (figure 2.2 and 2.3) showed us that smaller zeolite particle size and higher zeolite percentage replacement of cement resulted in less free water from the cement slurry, which is favorable.

The tabulated results (Table 2.1) of the compressive strength testing from the TerraTek Universal Testing Machine are as follows.

Table 2.1: Results of Compressive Strength Testing at 45°C

Zeolite	Replacement	Compressive Strength (psia)		
		5 micron	10 micron	44 micron
Chabazite	15%	712	660	318
	27.50%	1845	1519	512
	40%	NA	NA	1313
Mudhill Clinoptilolite	15%	429	338	260
	27.50%	594	533	228
	40%	NA	1263	221
Ferrierite	15%	342	269	331
	27.50%	491	302	227
	40%	505	297	194
NM1 Clinoptilolite	15%	292	324	210
	27.50%	285	328	230
	40%	NA	442	177
NM2 Clinoptilolite	15%	292	324	210
	27.50%	285	328	230
	40%	NA	442	177

The general trend observed suggests that a zeolite particle size of 5 microns provides the best compressive strength, and 40% replacement of the cement with a zeolite is ideal.

Next, it is important to compare the compressive strength of the cement slurry after it has been cured at different temperatures but has the same percentage of cement replaced by a zeolite by the weight of the blend of cement and zeolite (not counting any additives). This was done by curing the cement slurries at 45°F and 70°F and then comparing their respective compressive strengths.

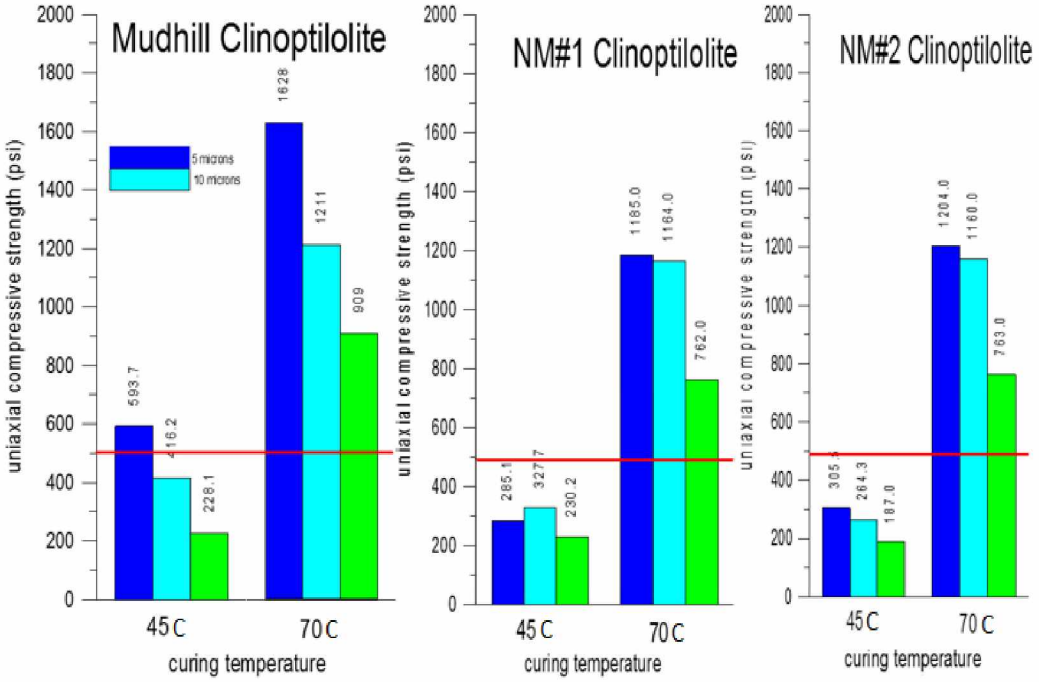

Figure 2.4: Bar graphs showing change in Compressive Strength with Curing Temperature (Patel, 2012)

The general trend observed indicated that a higher curing temperature results in a higher compressive strength of the zeolite blended cement. Once this was consistently established, testing was undertaken by mixing different additives to the cement slurries as well as observing the effects of mixing two different particle sizes of the same zeolite in a single cement blend.

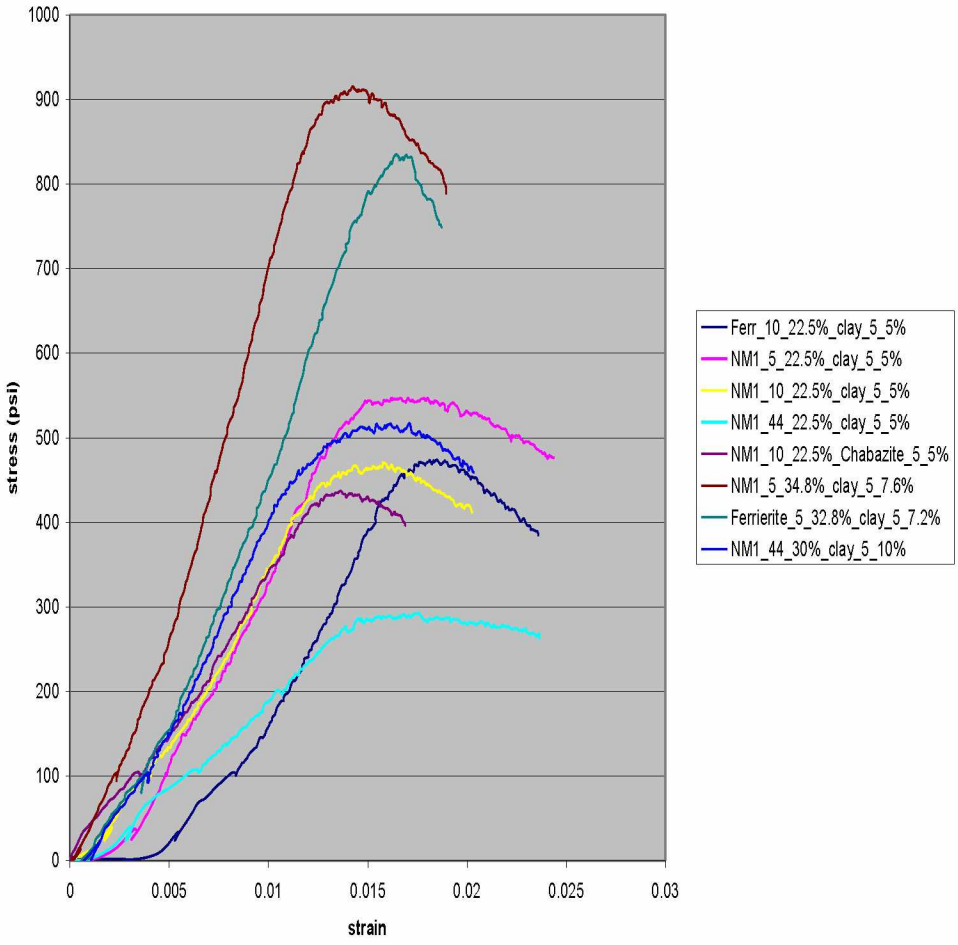

Figure 2.5: Stress-Strain Plots of Zeolite Blended Cement with a mixture of Montmorillonite Clay as an additive

The general trend observed suggested that additives rich in silica content helped increase the compressive strength of the cement blend. Since a blend of simply cement and zeolite particles barely manages to fulfill the strength and water loss requirements, it would be beneficial to use a system of additives to further augment these while at the same time improving the thixotropic behavior of the cement slurry, particularly in the case of the development of its consistency.

2.5 Evaluation of the Zeolites' Performance

- Chabazite: A high quality zeolite replacement, however, its high cost makes it unlikely to be economically viable.
- Ferrierite: Barely manages to fulfill the requirements. However, it is cost effective and may prove to be promising if a system of additives is employed.
- Mudhill Clinoptilolite: A good zeolite at lower particle sizes.
- New Mexico Mine #1 Clinoptilolite: Failed to meet the minimum compressive strength requirement of 500 psi. It will require a system of additives in order to be successful.
- New Mexico Mine #2 Clinoptilolite: Failed to meet the minimum compressive strength requirement of 500 psi. It will require a system of additives in order to be successful.

3. High Temperature-High Pressure Testing Experimental Design

This chapter discusses the high pressure – high temperature (HPHT) experiments conducted on the select zeolite blend samples that passed the initial screening. The experimental data from these HPHT tests presented in this report were obtained through my involvement with the cement project research group at UAF.

3.1 HTHP Compressive Strength Test using an Ultrasonic Cement Analyzer

The Chandler Engineering/AMETEK Model 4265-HT Ultrasonic Cement Analyzer (UCA) allows for continuous measurement of cement compressive strength as a cement sample cures under high temperature and pressure conditions. The machine does this in an indirect way by passing an ultrasonic signal (a sound wave with a frequency above the normal audible range of human hearing) through the cement sample, measuring the signal's transit time. As the sample hardens, the transit time diminishes. Algorithms developed and proven by the oil and gas industry are used to convert the measured transit time into compressive strength. The results are generated graphically on the coupled computer. Compressive strength is graphed as a function of time (compressive strength, in psi, on the Y-Axis, and time, in hours, on the X-Axis).

Figure 3.1: Chandler Engineering/AMETEK Model 4265-HT Ultrasonic Cement Analyzer with protective cage

Experimental Procedure:

1. Prepare the cement slurry as per instructions and condition it in the atmospheric consistometer.
2. Smear lithium grease or high temperature grease all around the inside of the bottom end cap, including the threads of the UCA cell. Now, place this cap in a vise.
3. Place a metal O-ring onto the cap with the steepest chamfered side pointed down, towards the end cap. Slide a rubber O-ring down around the metal O-ring and cover the outside of the rubber O-ring in grease.
4. Repeat the greasing procedure with the top end cap (the one with the handles and holes), taking care not to push grease into holes (the grease keeps cement from sticking, so be liberal).
5. Smear lithium grease onto the inside wall of the cylinder coating the wall (threads will be secured by attaching end caps).
6. Assemble the cement mold by joining the mold halves, holding them together with two rubber O-rings.
7. Smear red high temperature grease on outside and inside of mold.
8. Set assembled cement mold onto bottom end cap (there is no specific "top" or "bottom" to mold).
9. Using both hands, grasp the cylinder and screw onto bottom end cap, "snugging" only very slightly.
10. Set up the test on the computer, setting "ramp" for 4 hours and "temperature" to 300°F.
11. Pour cement slurry into mold, filling it 1/16" from the top.

12. Using a syringe, fill the space between the mold and the cell wall with water. Fill to 1/16" above the mold top, covering the cement.
13. Slowly screw down the top end cap, very gently "snugging" it (water will come out of the two large holes on the top).
14. Grasp assembled cell and place in UCA.
15. Install the L-shaped stainless steel pressure line and tighten in place using wrench.
16. Install the coiled stainless steel transducer assembly, tightening in place.
17. Install the black thermocouple line, but leave loose.
18. Switch the "Pump Water" rocker switch on – water will escape from the loose thermocouple connection, allowing air to be removed from cell.
19. Tighten thermocouple connection with wrench.
20. Switch "Pump" rocker switch on.
21. Use black "Pump Pressure Adjust" knob clockwise to increase the pressure to that required for the test to be initiated (the large blue "Relief Valve" knob is to be adjusted in concert here – it keeps a "ceiling" pressure set above that which is set by the black "Pump Pressure Adjust" knob).
22. Check that the computer shows a transit time of ~16 microseconds/hr.
23. Start the test and switch "Heater" rocker switch on.
24. For safety reasons, the UCA should not be left unattended until it reaches the set temperature and stabilizes at that point.

3.2 HTHP Consistency Testing

This test was carried out using a Chandler Engineering/AMETEK Model 8340 HTHP Consistometer.

Figure 3.2: Chandler Engineering/Ametek Model 8340 HTHP Consistometer

Experimental Procedure:

1. Apply a generous amount of lithium grease to the top cap threads. Invert the top cap and set it onto a mounting plate (studs on the plate will align with the holes in the cap).
2. Place the back-up plate concave up onto the top cap and a rubber diaphragm on top.
3. Place a metal ring onto the diaphragm with the tapered side down.
4. Invert the cylinder and screw onto top cap by hand, "snugging" slightly.
5. Apply lithium grease to paddle shaft at contact point of diaphragm and insert shaft first into the cylinder pushing it through the diaphragm.
6. Liberally apply lithium grease to threads of bottom cap and the inside surface of same cap. Do not grease the inside walls of cylinder, for cement would simply slide in place.
7. Screw the bottom cap onto the cylinder, gently tightening it.
8. Apply lithium grease to the threads of the top cap plug, filling bottom divot with grease.
9. Screw plug into top cap threaded hole, screwing in only finger-tight.
10. Remove assembled cup from holder, hold assembly by paddle shaft and spin cup – it must spin freely on the shaft.
11. Prepare the cement slurry and with the cylinder upside down, pour the slurry in while lightly tapping on outside of cylinder with wrench or small hammer, releasing air bubbles from the cement mix. Slurry should reach the first thread of the cylinder.
12. Screw bottom cap onto cylinder – if enough cement has been poured into cylinder, some cement will escape from top hole.
13. Screw the nut into the hole, "snugging" with wrench and remove any excess cement.

14. Per API specifications, take the assembled cylinder and start the test within 5 minutes. Here, the machine is cold and the curing chamber empty.
15. Unscrew the curing chamber cover, which will retract up hanging on the cable. With one hand on cover and one hand on boom arm, swing cover off to left side of machine.
16. Insert the ends of the longer bail (stainless steel looped hook hanging on front of machine) into the closer-spaced pair of holes on the cup's top end.
17. Lower cup into curing chamber, slightly wiggling cup as it descends. When it bottoms out, turn it clockwise using the bail. If the cup is in place it should turn clockwise but give resistance (the resistance felt is the motor being turned).
18. Remove the bail from cup and switch on the motor. Insert the smaller bail into the potentiometer and carefully lower potentiometer into the curing chamber.
19. Switch the "Cylinder" rocker switch to "Fill."
20. Swing black cover into place and carefully rotate the cover clockwise until the threads mate well. Before it stops turning, jolt the cover closed clockwise, ensuring a tight fit.
21. Plug in the thermocouple connection to the front of the machine (double-pronged receptacle) and insert thermocouple probe into top of cover.
22. Close the pressure relief valve and switch on the pump briefly until the reading reaches ~500psi. Now, switch the pump to "Auto."
23. Click "Start Test" button on the computer and switch on the timer, heater, and alarm.
24. Monitor the machine for at least 10 minutes, watching for oil leakage between black cover and steel collar (directly beneath the cover). Return every 5 minutes to watch for leaks until the machine is up to test pressure.

3.3 Thermal Conductivity Testing

This test is carried out using a core that has been cured under HTHP conditions in the Chandler Engineering Pressurized Curing Chamber (Model 1910). Since the entire cube of cement is used, there is no need to core it.

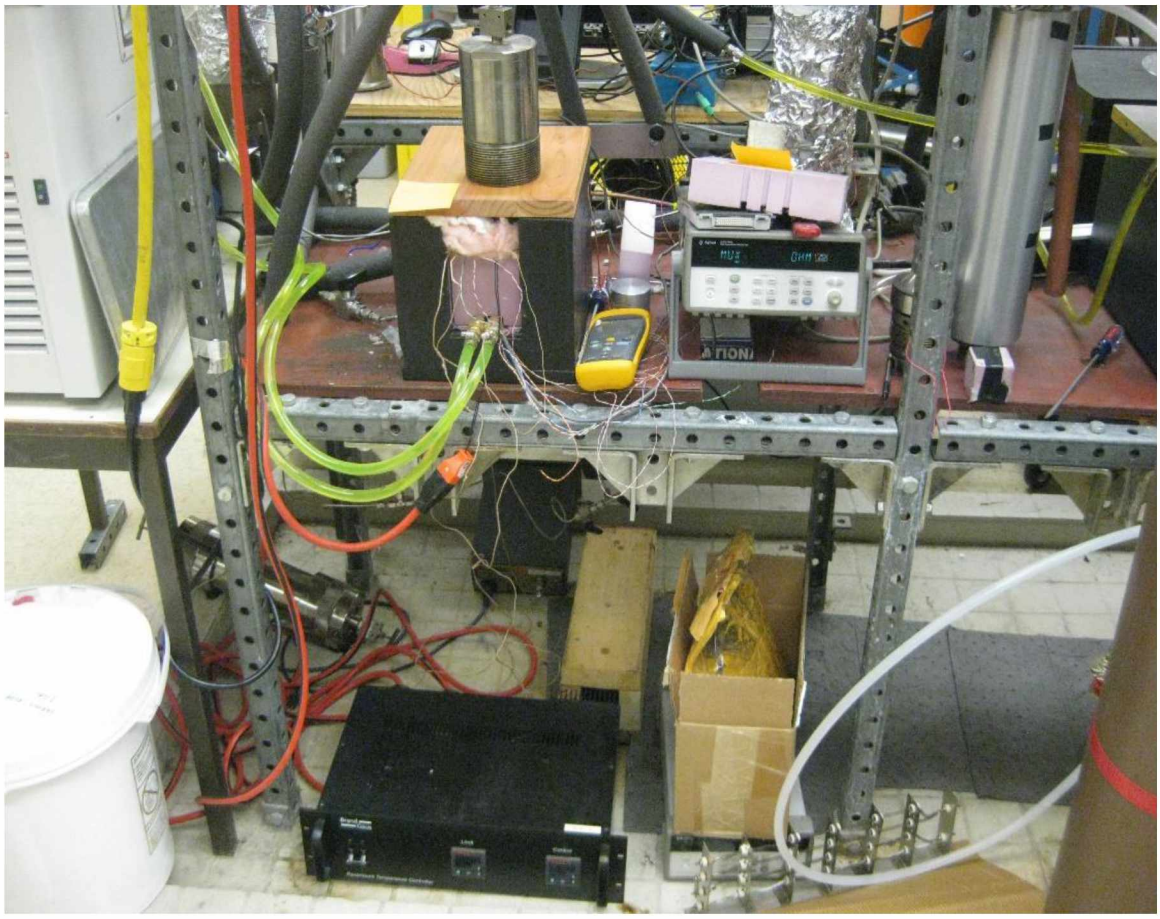

Figure 3.3: Thermal Conductivity Testing Apparatus

Experimental Procedure:

1. Use thermal paste to attach temperature sensors to two opposite sides of the zeolite cement cube.
2. Wrap the remaining sides of the cement cube with the insulation foam and place the cube in an insulated box. The box allows heat to be applied to the cube from only one direction. This ensures that while no heat escapes the cube, no external heat enters also.
3. Measure the temperature difference on either side of the zeolite cement cube as the starting point.
4. Begin applying heat to one side of the cube. The digital thermometer connected to the heat source (an induction coil) measures the heat input, while the temperature sensors on either side of the cement cube measures the amount of heat being transmitted through the cement.
5. Taking readings over a period will give us not only the amount of heat transmitted by the zeolite cement cube, but also the rate at which it is transmitted.
6. The temperature gradient and the heat flow rate are then used to obtain a measure of the thermal conductivity.

3.4 Carbonation Effects

This test was carried out by submerging cement core plugs in a brine solution within an accumulator. Carbon dioxide was then pumped into the accumulator to simulate the process of carbonation and nitrogen was used to maintain the accumulator at a high pressure condition. This accumulator was then placed within a Tenney FS202 Heating Chamber 145 to simulate a downhole high temperature condition. The importance of studying carbonation is to ascertain the cement integrity modification caused by carbon dioxide invading the cement core. Carbonation can lead to reduced cement strength and severely compromise the structural integrity of the cement which is highly unfavorable.

Figure 3.4: Tenney FS202 Heating Chamber 145

Experimental Procedure:

1. Saturate the cores with brine.
2. Place the cores within an accumulator immersed in brine. Each accumulator should have cement cores of each blend being tested.
3. Place the accumulators within the heating chamber and connect it to the pipe manifold, which is in turn connected to the cylinders of nitrogen and carbon dioxide.
4. Pressurize one accumulator using nitrogen and the other using carbon dioxide.
5. Care must be taken to ensure that the cylinders remain pressurized. As the brine and eventually the cores absorbs the gas, the pressure level will begin to drop.
6. At this point, more gas needs to be released using the manifold to ensure that the right cylinder is pressurized using the right type of gas.
7. The cores remain in this state for a week, after which they must be tested for carbonation changes. The cores are then removed, observed to see the effect of carbonation, and placed back in the accumulator.
8. The cores are then removed after a month and observed once more. More observations can be taken at a three-month interval and greater intervals if longer-term data is required. Proper planning is needed in these stages to ensure an adequate number of cores are prepared.

3.5 Fluid Loss Testing

Fluid retention by the cement is vital for the cement to maintain its compressive strength characteristics in the HTHP environment. This test allows the measurement of the amount of fluid lost from a particular zeolite cement sample under certain temperature and pressure conditions.

Figure 3.5: Fann HTHP Filter Press Series 387 (500ml)

Experimental Procedure:

1. Prepare the cement slurry and condition it in the atmospheric consistometer.
2. Place the screen towards the bottom of the cylinder and place O-rings on either end.
3. Seal the bottom of the cylinder with the cover and make a mark about one and a half inches from the top of the cylinder on the inside of the cylinder.
4. Pour the cement slurry into the cylinder up to the mark. The space remaining in the cylinder is to allow cement expansion while heating to HTHP conditions.
5. Seal the top with the appropriate cover and ensure that both ends are tightened.
6. Push down on the pressure indicator button on the top of the cylinder. It should depress easily, showing that the cylinder is currently not pressurized.
7. Place the cylinder in the heating chamber and connect the nitrogen gas manifold to the top and the bottom of the cylinder to pressurize the cylinder.
8. The pressure indicator button should rise up by itself and be impossible to depress.
9. Heat the cylinder and increase the pressure at the top of the cylinder to HTHP conditions as required by the test.
10. Attach the outflow pipe to the bottom of the cylinder and slowly open the bottom valve of the cylinder while starting a stopwatch.
11. At the 30-second mark, open the valve of the outflow pipe and allow fluid to flow out into a beaker. Once it stops flowing, shut the valve.
12. Consecutive readings are then taken in a similar fashion at the 1 minute, 5 minute, 10 minute, 15 minute, 20 minute, and 30 minute marks, each with a different beaker

to accumulate the outflow fluid. The fluid loss from the cement is the cumulative fluid accumulated in all the beakers combined.

13. Shut the valves at the bottom and the top of the cylinder, turn off the heating chamber, and let the cylinder cool. A fan can be used to speed up this process.
14. Once the internal temperature of the cylinder has returned to room temperature, the pressure can be relieved from the cylinder slowly.
15. Ensure that the pressure indicator button can now be depressed manually indicating that the pressure has been properly relieved.
16. Open the cylinder and remove the filter cake that is formed near the bottom of the cylinder and clean the apparatus for the next experimental run.

3.6 Viscosity and Gel Strength Testing

The viscosity and gel strength of a cement has a significant impact on the pumping of the cement and the speed at which it develops strength. Along with consistency data, it can provide valuable insight into the required pumping schedule of the zeolite cement. This test was conducted using a six-speed viscometer.

Figure 3.6: Chandler Engineering/Ametek Model 3506-110V Six-Speed Rheometer

Experimental Procedure:

1. Prepare the cement slurry and run it on the atmospheric consistometer for half an hour before pouring it into the viscometer cup. Place the cup securely on the viscometer plate.
2. Raise the plate so that the level of the zeolite cement in the viscometer cup is at the exact same level as the engraved line on the agitator, then take a measurement of the initial zeolite cement slurry temperature using a thermometer.
3. Start the viscometer at its lowest speed (3 rev/s) and allow the viscosity reading on the gauge to stabilize. Subsequent readings are then taken at 6 rev/s, 100 rev/s, 200 rev/s, 300 rev/s, and 600 rev/s while ramping up the speed.
4. The next set of readings are taken while ramping down the speed of the viscometer in the same order as the ramp-up, but going in the opposite direction.
5. Once all the readings for viscosity are obtained, the viscometer agitator is turned off and the cement sample is allowed to stand. The temperature is now measured.
6. The agitator is turned on again and set to 3 rev/s and readings are taken at the 10 second and 10 minute marks.
7. These readings are used to calculate the 10 second and 10 minute gel strength using equation 3-2, respectively, according to the formula provided below (Allen & Roberts, Prodcution Operations: Well Completions, Workover and Stimulation Volume 2, 1989).

Equation 3-1: Gel Strength Calculation

$$\tau\,(Pa) = 0.5099 * F * \theta$$

Where,

$$F = Torsion\ Spring\ Factor = 1$$

$$\theta = Viscometer\ Reading\ (in\ instrument\ degrees)$$

Note: This test was run under room temperature and pressure; however, since it was part of the secondary testing, it has been included under HTHP testing.

4. Results and Discussion of HTHP Testing

The preliminary stage of testing indicated that a 40% replacement of cement with a zeolite has the potential to form a good lightweight cement slurry. Therefore, HTHP testing focused on zeolite replacements at or near 40% of the cement using ferrierite, mudhill clinoptilolite, New Mexico Mine #1 clinoptilolite, and New Mexico Mine #2 clinoptilolite. Chabazite, despite its great potential due to the high compressive strength it displayed, remained significantly more expensive than the other options and unlikely to be an economically viable candidate. It was initially tested during the HTHP phase of testing but was then discarded in favor of pursuing cement blends containing the other zeolites.

Out of the remaining options, ferrierite was identified as the most promising candidate. This was due not only to its success during HTHP testing but also its favorable properties when used with additives.

4.1 Compressive Strength

Compressive strength is the capacity of a material to withstand loads that tend to reduce size. At an atomic level, when a material is compressed, the individual atoms that make up the material are forced closer together. This results in an increase in the repulsion among the individual atoms until failure occurs.

The strength properties of cement mixes can be variable at elevated temperatures and many common phase changes of the hydration products occur between 200°F and 250°F. The HTHP phase of testing revealed the strength transitions that took place in the cement, particularly when these phase changes were taking place. Though the long-term behavior

of the cement remains occluded, this phase of testing provided accurate data regarding the behavior of the cement over periods up to a week.

Of particular interest was the stabilized zone of cement strength that starts to set in around the 30 – 100 hour mark, which is between one and four days. Therefore, various blends of cement were tested one after the other in the Ultrasonic Cement Analyzer (UCA) up to a period of 7 days, and then the results were compared against each other.

The cement blends differentiated themselves from each other in a number of ways. These were:

- They used different zeolite as a replacement for the cement in the slurry,
- The amount of cement being replaced by a zeolite,
- The system of additives, and,
- The overall density of the cement slurry: in most cases, it was 13.5 ppg, but in some cases, it was lower than 13.5 ppg.

The UCA emitted acoustic waves and measured the transit time taken by the wave to pass through the cement. The harder the cement was, the shorter the time taken by the wave to traverse the cement sample and with it, the higher the compressive strength of the cement blend. Some of the tests were halted when it was ascertained that a stable cement strength had been attained and further testing would not reveal any significant change in the cement strength.

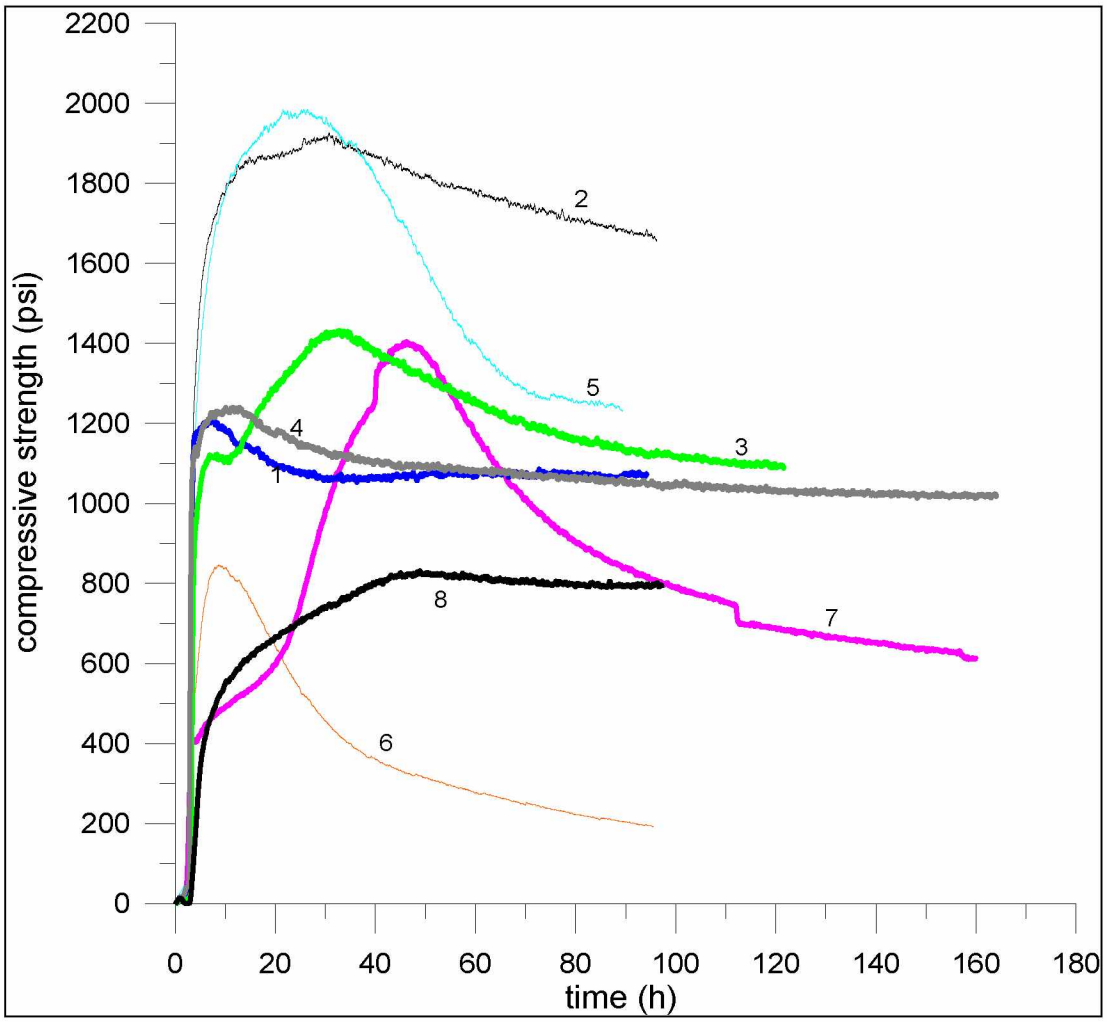

Figure 4.1: HTHP Ultrasonic Cement Analyzer (UCA) test results for testing conducted at 300°F and 5000psi

Figure 4.2: Legend of Cement Blends for Figure 4.1

From the previous diagrams, we can see that the most promising candidate out of the potential zeolites is ferrierite. This is because it stabilizes at a higher compressive strength than the other zeolites under the same temperature and pressure conditions.

4.2 Consistency

Consistency is defined as a rheological property of matter related to the cohesion of the individual particles of a given material, its ability to deform, and its resistance to flow. The consistency of cement slurries is determined by thickening time tests in accordance with API Recommended Practice 10B and is expressed in Bearden units (Bc) of consistency.

The pumpability of a cement depends heavily on the consistency profile that it displays over a period of time in which there are variations in the prevalent temperature and pressure conditions. If the cements develop a high consistency too quickly, it will not reach the zone that is intended to be cemented. This would result in regions within the well where there is insufficient support and sealing. The lack of zonal isolation compounded by the weakness of the well can seriously damage the overall integrity of the well and may even lead to well failure over time.

Using a 5 micron particle size, ferrierite proved difficult to handle since it thickened too quickly. Hence, to ensure that the change in consistency of the cement over time was more acceptable, the 40% ferrierite was done as a 30% replacement using 5 micron size ferrierite and a 10% replacement using 44 micron ferrierite. The end result was a lightweight cement slurry that had much better consistency. However, the cement consistency still ramped up too fast and it would be much more desirable to have the onset of high consistency be

delayed further. At this point it was noted that the 5 micron particles provided much better compressive strength and the infusion of 44 micron particles into the cement slurry mixture had reduced the overall compressive strength of the zeolite blended cement. Therefore, further delaying the onset of high consistency of the lightweight cement would require a retarder, rather than increasing the amount of 44 micron ferrierite while simultaneously decreasing the amount of 5 micron ferrierite.

To offset the decrease in compressive strength, the silica content of the cement needed to be increased. This was done through the additives MDE (Moltan Diatomaceous Earth or Montmorillonite Diatomaceous Earth) and MINUSIL (Minute Silica), a very fine-grained silica flour.

The retarders that were tested were:

- Tartaric Acid (TA),
- Sodium GlucoHeptonate (Na GluHep), and,
- Sodium TetraBorate (Na tetraborate).

The various retarders were tested and using a process of trial and error, the appropriate amount and type of retarder to be used was found. The retarders were mixed as a percentage of the weight of the blend of zeolite and cement, i.e., by weight of blend (BWOB). The cement mixture itself was kept constant when comparing different retarder concentrations. Initially, testing was carried out on a cement blend containing a 40% replacement of cement using 10 micron ferrierite. However, as compressive strength testing results were obtained,

most of the testing was then done using cement replacements of 30% 5 micron ferrierite, 10% 44 micron ferrierite, 20% MDE, and 20% MINUSIL.

Some of the other zeolites were also tested using the same overall 40% cement replacement; however, the focus of the testing remained on ferrierite. The change in consistency of the cement slurry was used to ascertain the thickening time of the particular blend of zeolite and cement.

It is important to note why so much importance was placed on testing ferrierite before any of the other zeolites. Since multiple experiments were conducted simultaneously, results from other tests allowed for the honing in of testing focus on ferrierite. Since multiple tests showed that ferrierite held the greatest promise, it became important to test various ferrierite-cement blends thoroughly to find the zeolite cement mixture that could fulfill the API requirements.

Allocation of time becomes particularly important when considering the lengthy nature of the individual tests and the large number of tests that need to be performed in any trial and error process in order to arrive at useful information. Therefore, constant honing of focus in planning experimental cement blends helped arrive at the desired cement blend in a timely fashion.

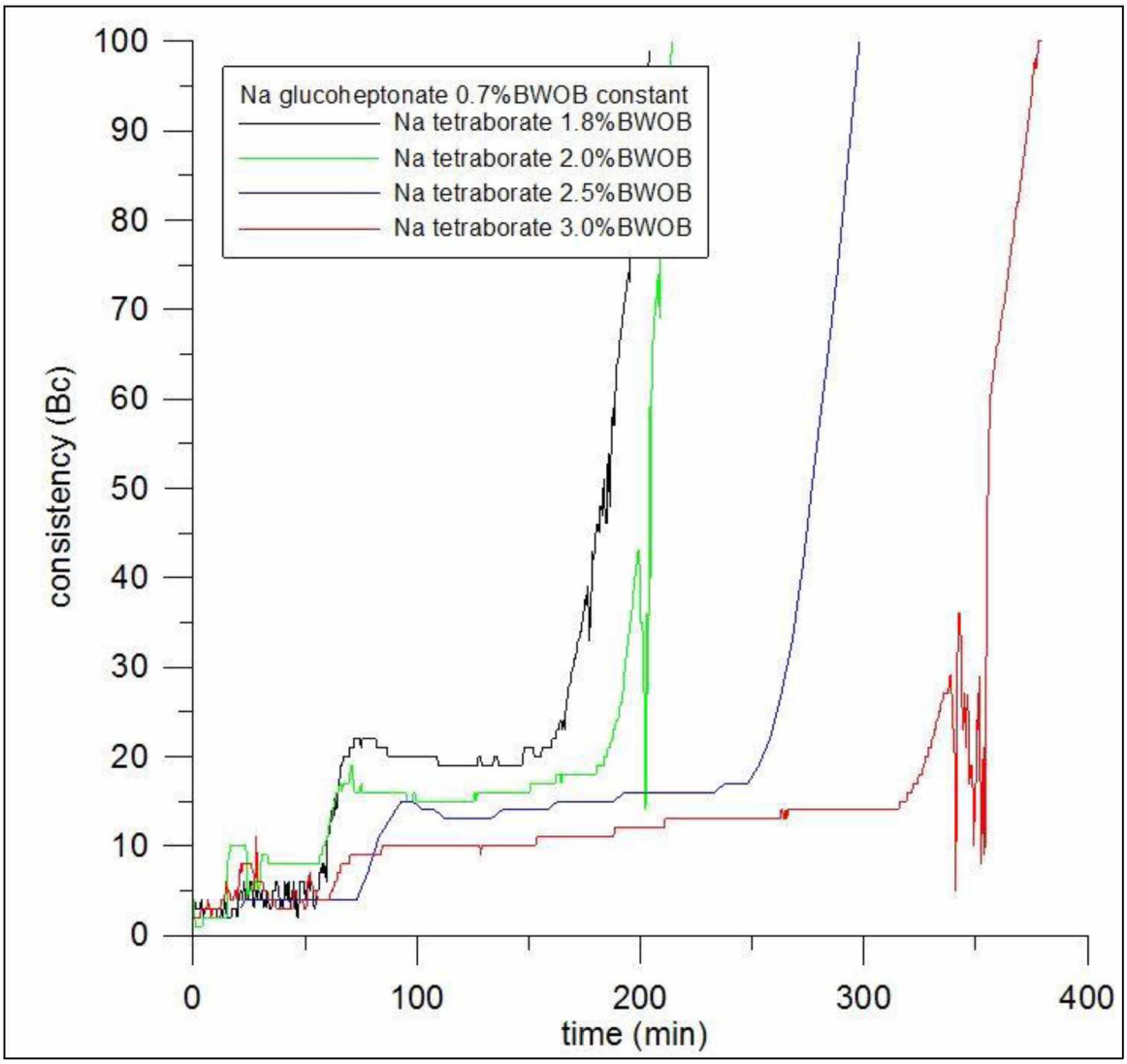

Figure 4.3: Consistency profiles showing the influence of sodium tetraborate on the slurry thickening profiles (sodium glucoheptonate was held constant at 0.7% BWOB)

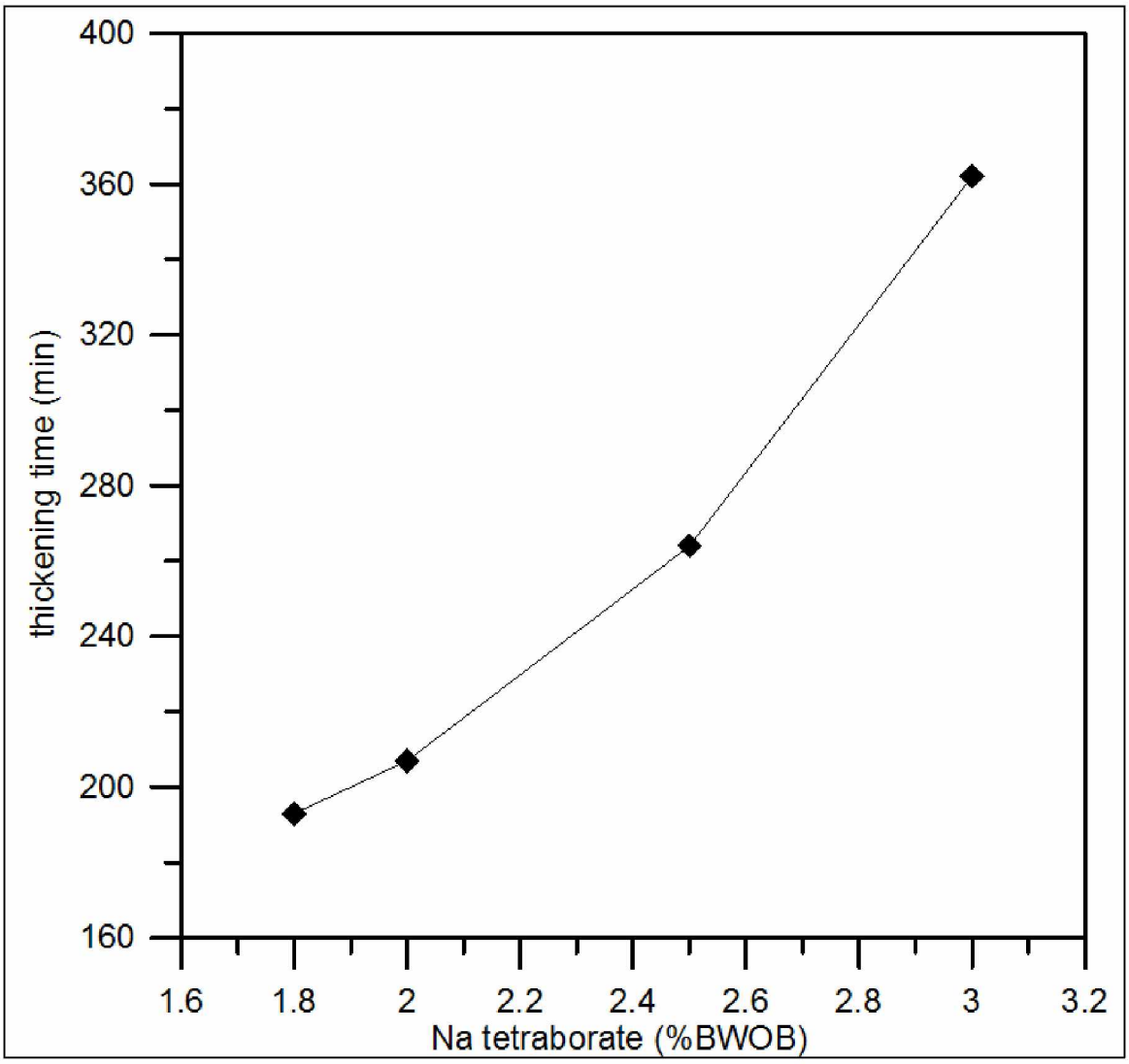

Figure 4.4: The thickening time influence of varying concentrations of sodium tetraborate with sodium glucoheptonate held constant at 0.7% BWOB

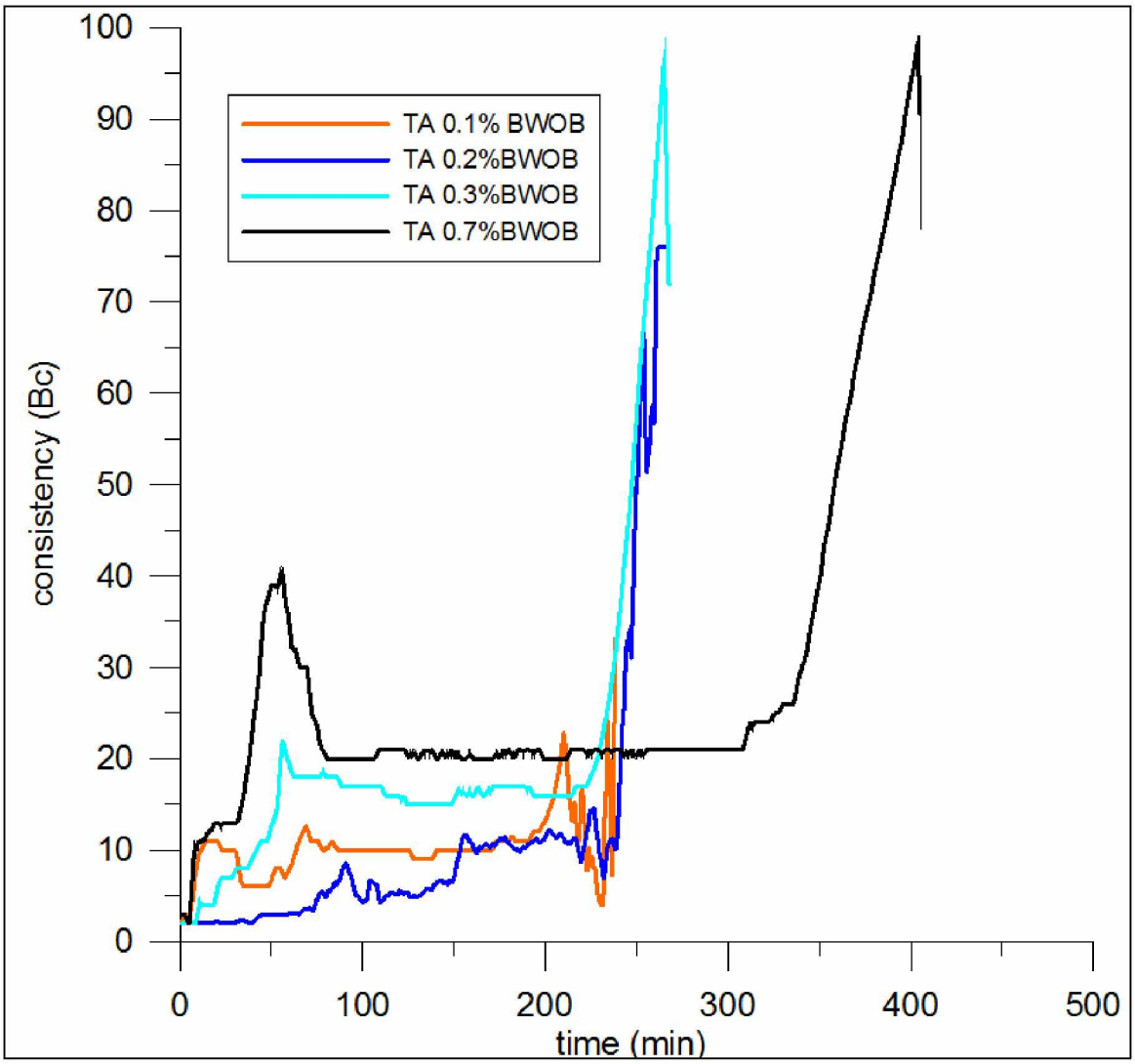

Figure 4.5: Consistency profiles for varying tartaric acid concentration with a constant concentration of 0.7% sodium glucoheptonate and 2.0% sodium tetraborate

Some tests were carried out at 300°F and 14,000 psi, but most tests were carried out at 400°F and 14,000 psi. Both the temperature and the pressure were slowly ramped up to the final temperature and pressure conditions over the course of an hour.

Since it was observed that tartaric acid (TA) had a large effect on the consistency profile of the cement, it was deemed important to pair the tartaric acid with a secondary retarder. This secondary retarder would act as a means of fine-tuning the consistency profile, which is not possible using tartaric acid alone, since it caused only large changes in the consistency profile one way or the other.

Of sodium tetraborate and sodium glucoheptonate, the latter proved to be more versatile. In addition, since sodium glucoheptonate can be easily procured in liquid form (as manufactured by a company called RussTech Admixtures), it was easier to use in forming a homogenous distribution of the retarder within the cement slurry.

The final retarders to be used as additives to the lightweight cement blend were found to be a 0.8% addition of tartaric acid by weight of the blend (BWOB) paired with a further addition of 0.8% sodium glucoheptonate BWOB.

4.3 Fluid Loss

Over the course of a cementing operation, there is a chance that the fluid phase will separate from the cement slurry. This can cause a number of problems. Other than the obvious increase in the Equivalent Circulating Density (ECD) of the cement slurry, there is a possibility of the cement undergoing flash setting due to dehydration, or formation damage taking place due to the lost circulation. In addition, the reduction of the slurry volume can compromise the structural integrity of the well due to a reduction in the effective hydrostatic pressure that in turn reduces the strength of the cement. Furthermore, migration

paths might be created through which the formation fluid could possibly pass, thereby allowing channeling between the casing string and the cement.

To avoid such an eventuality, Fluid Loss Additives (FLAs) are used to limit if not prevent the separation of the fluid phase from the cement slurry. Two different fluid loss additives were tested, namely:

- FL-17, and,
- FL-24.

The API standards for oil well cements allow for the loss of 100 ml of fluid from a 500 ml cement slurry sample over the course of 30 minutes. This fluid loss measurement is done before the cement slurry has been given the opportunity to gain higher consistencies. The test itself is carried out at a pressure of about 1100 psi and a temperature between 300°F and 400°F.

The testing described here was carried out on a cement slurry containing a cement replacement of 30% 5 micron ferrierite, 10% 44 micron ferrierite, 20% MDE, and 20% MINUSIL. In most of the cases, the cement slurry was maintained at a density of 13.5 ppg. However, some tests were also conducted at lower densities, usually about 13 ppg, to study the feasibility of making the cement even lighter than it already was. It was observed that the 13 ppg density displayed unfavorable characteristics in terms of fluid loss. This was consistent with similar testing done for other cement properties, such as the compressive strength and the consistency.

Table 4.1: Summary of Fluid Loss Characteristics

Density (ppg)	Cement	Na glucoheptonate (Russtech)	Tartaric acid	FL-17	FL-24	API fluid loss (ml/30min)
13.5	H	0.8%	0.8%	0.75%	0.75%	96
13.5	H	0.8%	0.8%	1.0%	1.0%	118
13.5	H	0.8%	0.8%	1.5%	1.5%	73
13.5	H	0.8%	0.8%	0.5%	1.5%	74
13.0	H	0.8%	0.8%	0.5%	1.5%	209

The addition of Fluid Loss Additives (FLAs) significantly increased the consistency of the cement slurry. In fact, the cement slurry viscosities were sufficiently high (60 – 90 Bc) to make the use of such additives impractical above 2% BWOB.

Table 4.2: Effect of Retarders on Consistency and Thickening Times

Additives: retarders and fluid loss				Time (min)		
Na GluHep	TA	FL-17	FL-24	30 Bc	70 Bc	100 Bc
0.8%	0.8%	0.75%	0.75%	679	715	715
0.8%	0.8%	0.50%	1.50%	448	485	485

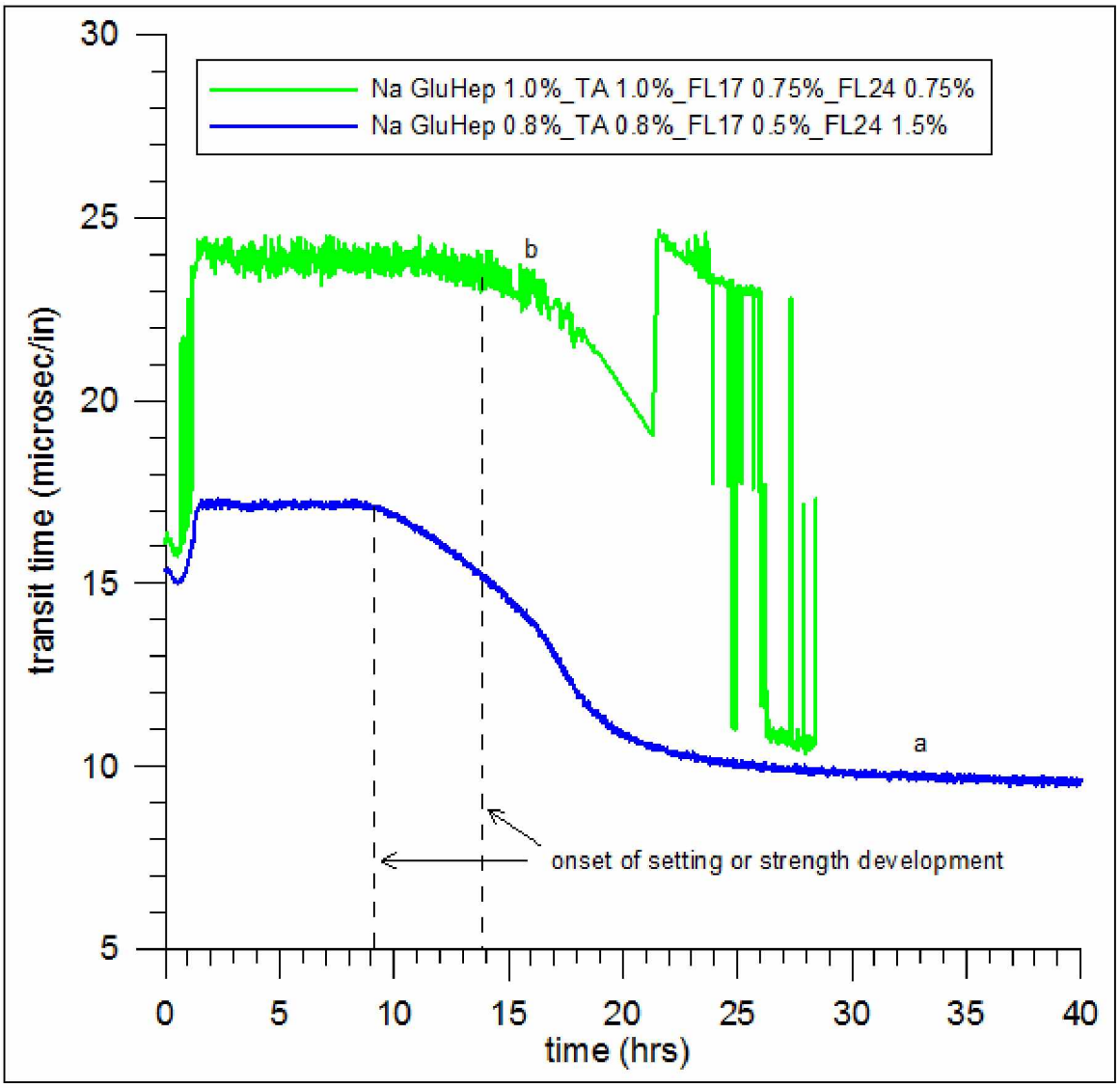

Figure 4.6: UCA results depicting Time vs Transit Time

As we can quite clearly observe, using an addition of FL-17 at 0.5% BWOB and FL-24 at 1.5% BWOB, we get the lowest possible fluid loss while keeping the cumulative amount of Fluid Loss Additives (FLAs) less than or equal to 2% of the total weight of the blend. Furthermore, using this FLA system, we can get the cement to thicken within 8 hours to 100 Bc, which is long enough to properly pump the cement, but is also short enough so

that the Waiting On Cement (WOC) time is minimal. This is favorable, as WOC is a wasted expense during well construction due to the time in which work cannot take place on the well. Importantly, this FLA system has a lower transit time throughout the entire period of observation, which indicates a higher compressive strength of the lightweight zeolite cement blend.

4.4 Effects of Carbonation

An important function of well cement is to provide zonal isolation. Therefore, it is important for the cement to have high structural integrity. The integrity of the cement can get compromised over time due to the effect of carbonation and hence, it is important to try and gain an understanding of the degree to which the cement can be expected to undergo carbonation. Cores were made from cement slurries cured under HTHP conditions and then maintained under HTHP conditions in accumulators. These cores were then subjected to carbonation by submerging them in an Ormat/CO_2 brine mixture under HTHP conditions. The cores were cut open and treated with phenolphthalein solution to study the degree to which carbonation had taken place. Cores of the same blend but carbonated for different periods were used in this test.

The cement slurry described henceforth as Fmix1 is a cement slurry containing a cement replacement of 30% 5 micron ferrierite, 10% 44 micron ferrierite, 20% MDE, and 20% MINUSIL, along with an addition of 0.8% BWOB each of tartaric acid and sodium glucoheptonate as well as an FLA addition of 0.5% BWOB FL-17 and 1.5% BWOB FL-24.

Table 4.3: Summary of properties of Fmix1 cured at 300°F for 3 weeks

		1 week		3 week	
	Initial	Ormat brine/CO_2	Control	Ormat brine/CO_2	Control
q_u (psi)	6484	3968	5091	3233	3652
E (ksi)	1243	831	933	828	556
ν	0.33-0.38	~0.28	~0.38	~0.40	0.27

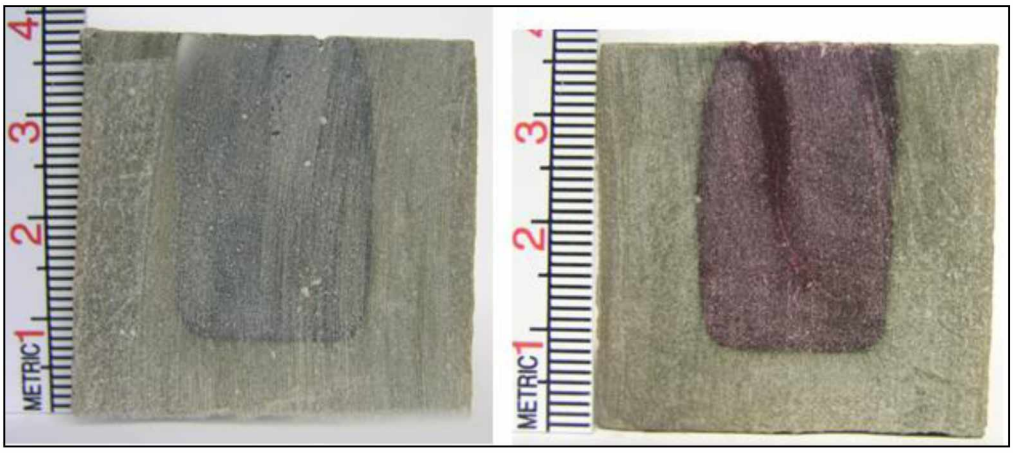

Figure 4.7: Fmix1, 1 week cure in Ormat brine/CO2 showing the altered zones including natural state (left) and treated with phenolphthalein (right)

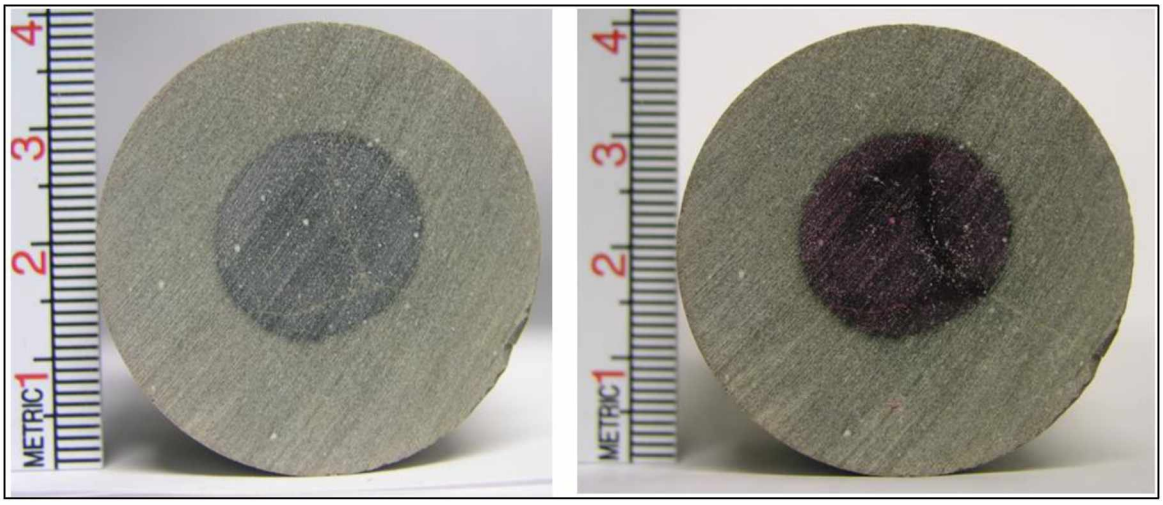

Figure 4.8: Cross-sectional views of sample cured in Ormat brine/CO_2 showing the altered zones including natural state (left) and treated with phenolphthalein (right)

5. Cement Cost Calculation

It is not sufficient for the lightweight cement blend to meet the API standards set out for oil well cements. It can only become a commercial success if it is economically viable to implement. Hence, an economic analysis was conducted to investigate the viability of the cement for use in HTHP oil and geothermal wells.

In order to carry out the study, the various components of the overall cost of the cement are categorized into two broad groups, namely, the 'cement costs' to represent the cost of the cement itself and the 'associated costs' to represent the costs associated with carrying out the cementing operation. In addition, to represent properly the variability that cementing operations can have, instead of simply adding up the associated costs of cementing, a Monte Carlo simulation is performed. The individual associated costs are varied by a factor of 10% using a randomized function to generate the data points necessary to carry out the Monte Carlo simulation. The mean of the sum of costs obtained from the Monte Carlo simulation is taken as being more representative of the actual reality of cementing a well.

5.1 Associated Costs of Cementing

The associated cost includes the cost of a cementing operation, but not the cost of the cement itself. This cost varies greatly depending on the type of cementing job being done, the equipment being used, and the time it takes to complete the job. Other factors might also come into play, such as the differences in Waiting On Cement (WOC) time depending

on the type of cement being used. However, the aforementioned factors remain the most important ones in modifying the price of the cementing operation.

For ease of calculating the associated costs of cementing a well, portions of the cost have been categorized into sections according to the nature of the cost (U.S Department of Energy). These broad categories are:

- Rig Costs,
- Operation Costs,
- Crew Costs, and,
- Equipment Costs.

Rig Costs

Rigs are rented out for a daily rate. The number of hours that the rig has been in use are added together, divided by 24, and then rounded up to the nearest whole number to get the number of days for which the rig must be rented. Even if an entire day is not utilized, it is added to the rig rent cost as per the daily rate in accordance with standard industry practice.

Operation Costs

The various components considered in the operation costs were calculated on a daily basis. The daily cost was then multiplied with the rounded up number of days for which the cementing operation took place in a similar manner as when calculating the rig costs. It was important to round up the number of days because when equipment is leased out by oilfield service providers, it is customary to bill an entire day even if the tool was not used for the entire day.

- Fuel

For example, for a 2200 HP rig, the fuel consumption was calculated as follows:

$$Cost\ of\ Fuel\ \left(\frac{USD}{day}\right)$$

$$= 1000\ (HP)\ x\ 0.45\ \left(\frac{lbs}{HP.hr}\right)\ x\ \frac{1}{7}\left(\frac{gallons}{lbs}\right)\ x\ 3\ \left(\frac{USD}{gallon}\right)\ x\ 24\ \left(\frac{hr}{day}\right)$$

$$= 4628.571429\frac{USD}{day}$$

0.45 pounds per HP-hour was obtained from a Rolls Royce comparison of a turboprop engine to gasoline engine fuel consumption efficiencies. The rig engine was matched to the most similar engine as far as application is concerned.

7 pounds per gallon is the fuel density obtained from the Department of Motor Vehicles' study materials for CDL (Commercial Driving License) tests.

Since the average retail price of fuel in U.S Dollars (USD) ranged from 2.6 USD/gallon to 3.4 USD/gallon from one U.S state to the next in 2014, the average (3 USD/gallon) was used in the calculation. The fuel consumed is used to run the rig itself and all the equipment that it powers such as the cement mixing units and cement pumps.

- Water

One of the major components used in cement is water. Besides this use, the crew uses water throughout the rig and the camp for a variety of operations not limited to cementing. Hence, it is counted as an associated cost.

- Electric power

Electric power is needed to run the computers, lights, and climate control that are not directly powered by the rig. This includes everything in the on-site crew quarters. Electric power separate from the rig is also required for building effective fire response and suppression systems.

- Camp Expense

This is the daily cost of maintaining the erected crew quarters and assorted offices out of which field personnel operate.

- Administrative Overhead

This cost is not directly linked to the production of a good or service. In the case of oilfield operations, this primarily refers to legal and auditing fees as well as the cost required to provide security to the field location through surveillance systems or other means as necessary.

- Miscellaneous Transportation

This refers to the cost of transporting the cement to the field site and the subsequent loading and unloading.

- Site Maintenance

The field site, once established, must be constantly maintained. Health, Safety, and Environment (HSE) scrutiny ensures that there is no contamination outside the secured waste pits. The recovery of topsoil in preparation for abandonment factors into this cost.

- Waste Disposal and Cleanup

Proper cementing procedures account for thorough cleanup. Cement, once hardened, can easily render most machines inoperable. Hence, particular attention is given to ensuring there are no clogs in mixing and pumping lines and that filter screens are regularly changed. Along with these, the cost to dispose of the waste in on-site waste pits or off-site safe landfills factors into this cost.

Crew Costs

First, the composition of a cementing team was determined and their individual hourly pay rates were noted (Glassdoor, n.d.). It is important to note here that only the salary has been considered and not the overall cost of employing the cementing crew which would include the cost of benefits. Therefore, the overall cost as shown as the crew costs may be underestimated leading to the overall cost of using the cement to be slightly lower than can be expected in a real world scenario.

Table 5.1: Crew Salary Costs

Role	Hourly Rate	
Truck Workers		
Mixing Truck Operator	33	(50K/yr.)
Pumping Truck Operator	33	(50K/yr.)
Rig Floor Workers		
Cementing Operator	55	(85K/yr.)
Cementing Operator Assistant	52	(80K/yr.)
Engineering		
Field Engineer	55	(85K/yr.)
Service Supervisor	77	(120K/yr.)
	305	USD/hr.

Next, the overall number of hours each of these workers are on-call is ascertained. Multiplying this with the number of hours worked gives us the cost of personnel for the cementing operation.

Equipment Costs

The equipment cost takes into account the cost of operating and/or renting the cement mixing and cement pumping trucks. In addition, the cost of scratcher, centralizer, float, and guide shoe, as well as top and bottom plugs for the cement job, usually falls on the cementing team even though some of these instruments are run by the drilling crew. This is because these instruments play a big role in ensuring that the cementing job takes place without any problems and the hole is ready for drilling to commence as soon as the waiting on cement (WOC) time is over.

5.2 Cement Costs of Cementing

The cement costs of cementing include the cost of the lightweight zeolite cement itself. The calculation starts out by finding out the quantities of each individual component required to form the dry mix of the cement and then calculates the water requirements to obtain a cement slurry of the desired density. By ascertaining the cost of each component and adding them to one another, the overall cost of the zeolite cement for a certain amount of cement slurry is obtained. Once the volume of the cement slurry produced is calculated, we can find out the cost per unit weight of the dry mix as well as the cost per unit volume of the cement slurry. This cost generally remains constant for all jobs done using the type of cement for which the calculations have been performed.

Calculation of Quantities of the Components of the Dry Mix

Desired weight of solids = 510 gm

- Ferrierite (5μm): 30% replacement = 0.3 x 510 = 153 gm
- Ferrierite (44μm): 10% replacement = 0.1 x 510 = 51 gm
- Cement: (100% - 40% = 60%) = 0.6 x 510 = 306 gm

  [153 + 51 + 306 = 510gm]
- MDE: 20% by weight of cement = 0.2 x 306 = 61.2 gm
- MINUSIL: 20% by weight of cement = 0.2 x 306 = 61.2 gm
- Tartaric Acid (TA): 0.8% by weight of blend= (0.8/100) x 510 = 4.08 gm

- Sodium Glucoheptonate: 0.8% by weight of blend = (0.8/100) x 510 = 4.08 gm
- FL-17: 0.5% by weight of blend = (0.5/100) x 510 = 2.55 gm
- FL-24: 0.5% by weight of blend = (0.5/100) x 510 = 2.55 gm

Calculation of the Water Requirement

Let the volume of the zeolite, cement and water be v_{zi}, v_c, and v_w, respectively.

$$\therefore \textit{The density of the slurry can be expressed as:}$$

$$\rho = \frac{Total\ Mass}{Total\ Volume} = \frac{\sum m_{z_i} + m_c + m_w}{\sum v_{z_i} + v_c + v_w}$$

$$Now,\ Volume = \frac{Mass}{Density},\ so\ we\ have:$$

$$\Rightarrow \rho = \frac{\sum m_{z_i} + m_c + m_w}{\sum \frac{m_{z_i}}{\rho_{z_i}} + \frac{m_c}{\rho_c} + \frac{m_w}{\rho_w}}$$

$$Now,\ Density\ of\ a\ Fluid = Water\ Density\ x\ Specific\ Gravity,$$

$$\Rightarrow \rho = \frac{\sum m_{z_i} + m_c + m_w}{\sum \frac{m_{z_i}}{\rho_w \gamma_{z_i}} + \frac{m_c}{\rho_w \gamma_c} + \frac{m_w}{\rho_w \gamma_w}}$$

$$\rho_w = 1\frac{gm}{cc} and\ \gamma_w = 1.0$$

$$\Rightarrow \rho = \frac{\sum m_{z_i} + m_c + m_w}{\sum \frac{m_{z_i}}{\gamma_{z_i}} + \frac{m_c}{\gamma_c} + m_w}$$

$$\Rightarrow \rho\left(\sum \frac{m_{z_i}}{\gamma_{z_i}} + \frac{m_c}{\gamma_c}\right) + \rho m_w = \sum m_{z_i} + m_c + m_w$$

$$\Rightarrow m_w(\rho - 1) = \sum m_{z_i} + m_c - \rho\left(\sum \frac{m_{z_i}}{\gamma_{z_i}} + \frac{m_c}{\gamma_c}\right)$$

$$\therefore m_w = \frac{\sum m_{z_i} + m_c - \rho\left(\sum \frac{m_{z_i}}{\gamma_{z_i}} + \frac{m_c}{\gamma_c}\right)}{(\rho - 1)}$$

Calculation of the Cement Volume

$$\therefore Therefore,\ total\ volume\ of\ cement\ produced = \frac{Total\ Mass}{Density}$$

$$= \frac{510\ x\ 397.96}{13.5ppg\ x\ 0.119826427\frac{\frac{gm}{cc}}{ppg}}$$

$$= 560.25\ cm^3$$

Calculation of the Cement Costs

Adding up the individual costs, as seen in the last column of the following table, we arrive at the total cost of the cement slurry.

Table 5.2: Outline of the Cement Costs of Well Cementing using a Zeolite Cement

Zeolite Cement Mixture (@ 13.5 ppg)				
Component	Particle Size (microns)	Quantity (lb)	Price (USD / lb)	Cost (USD)
Ferrierite	5	0.337	0.200	0.067
Ferrierite	44	0.112	0.200	0.022
MDE		0.135	0.349	0.047
MINUSIL		0.135	3.166	0.427
TA		0.009	17.500	0.157
Na GluHep		0.009	0.350	0.003
FL 17		0.006	7.510	0.042
FL 24		0.017	7.510	0.127
Cement H		0.675	0.063	0.042
Water		0.877	0	0

The cost of the water is counted as being a part of the associated costs, since water is used throughout the rig and not just in the preparation of the cement slurry. Therefore, the cost of water is taken to be nil here in the calculation of the cement cost. Therefore, the lightweight zeolite cement will cost 0.936 USD for 510 gm of dry mix (yielding a cost of 1.435 USD/lb) or for 560.25 cm^3 of cement slurry (yielding a cost of 47.300 USD/ft^3). When calculating the cost for larger quantities of cement, it is possible to round off the costs without introducing too great an inaccuracy in the calculations.

6. Economic Analysis

The economic analysis of the cement was carried out using a number of case studies. In each case, an example was taken and the cost of well cementing using a conventional Class H cement was calculated, along with the cost of well cementing using the lightweight zeolite cement blend.

6.1 Case I: Oil Well Cementing

In Case I, an example was framed to mimic the conditions in which the cement is expected to perform based on its technical specifications. The cement must be economically viable to be considered a success.

Problem Statement

A vertical well with a total vertical depth of 8000 ft. is to be cemented with a 3000 ft. cement rise behind the casing from the bottom of the wellbore. The bottom hole temperature is 300°F. Assume a spiral centralizer is present on the casing to ensure proper flow and bonding of the cement. The drilled hole size (gauge) is 10.75'' and the casing size is 8.675'' (ignore couplings). Use a fill-up factor providing 50% cement excess and calculate the cost difference between using Fmix1 as compared to standard cement.

Solution

From the previous chapter, we already have the cement cost of the zeolite cement. Using the same method, we can calculate the cement cost of a class H cement at 18 ppg, which is standard for most jobs like those described in the problem.

Table 6.1: Outline of Cement Costs using a Class H cement

Only Class H Cement (@ 18 ppg)			
Component	Quantity (lb)	Price (USD / lb)	Cost
Cement	1.124	0.063	0.070
Water	0.317	0	0

Therefore, the class H cement will cost 0.070 USD for 510 gm of dry mix (yielding a cost of 0.063 USD/lb) or for 403.36 cm^3 of slurry (yielding a cost of 3.552 USD/ft^3).

Associated Costs

For Class H cement, the Monte Carlo Simulation yields an associated cost of approximately 475,641 USD as shown in Figure 6.1.

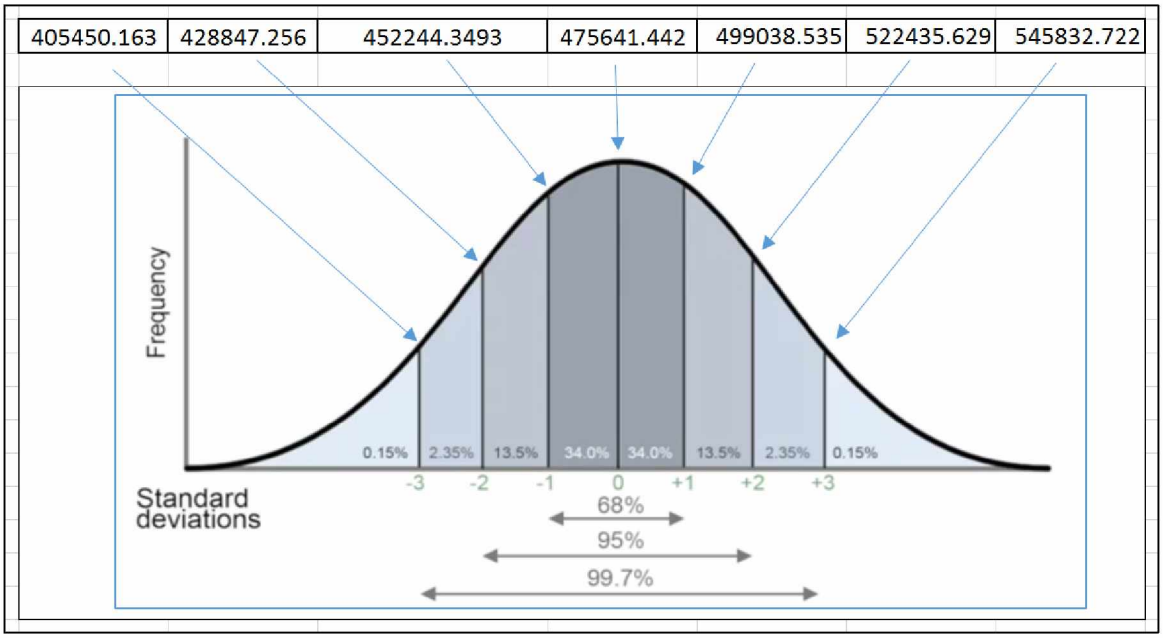

Figure 6.1: Monte – Carlo Simulation for Case I Class H Cement Associated Costs

For lightweight zeolite cement, the Monte Carlo Simulation yields an associated cost of approximately 247,570 USD as shown in Figure 6.2.

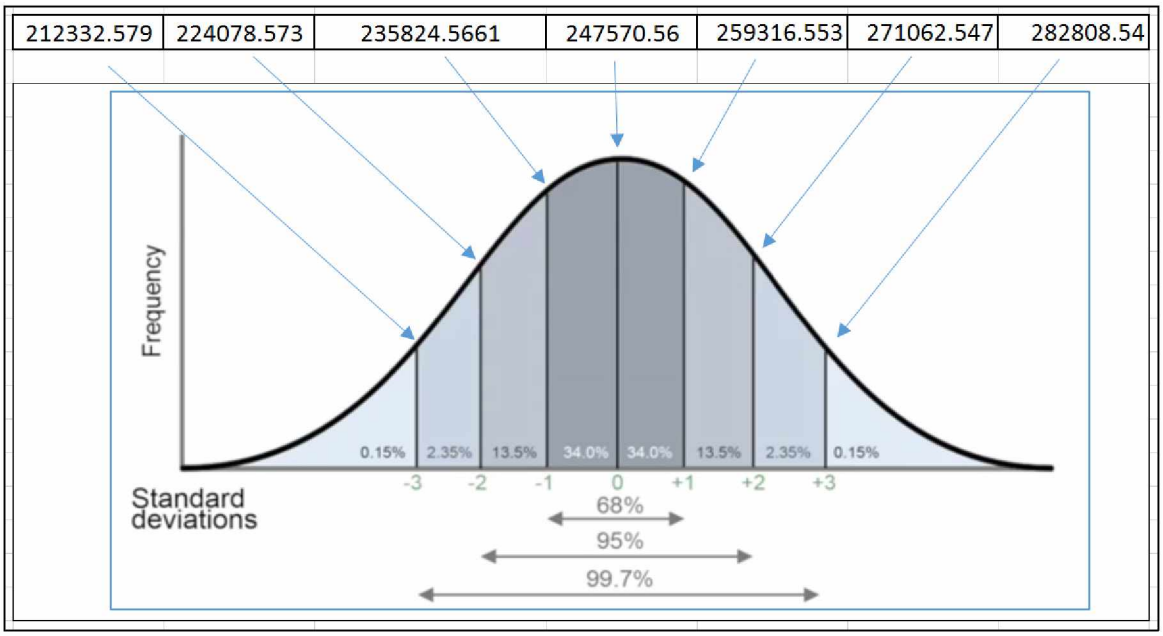

Figure 6.2: Monte Carlo Simulation for Case I Zeolite Cement Associated Costs

Sensitivity Analysis

The sensitivity analysis was done for the associated costs. Tornado plots were constructed with and without the rig costs. The rig costs are far greater than the other associated costs; therefore, it was important to reconstruct the tornado plots without the rig costs so that the other costs could be easily compared with one another.

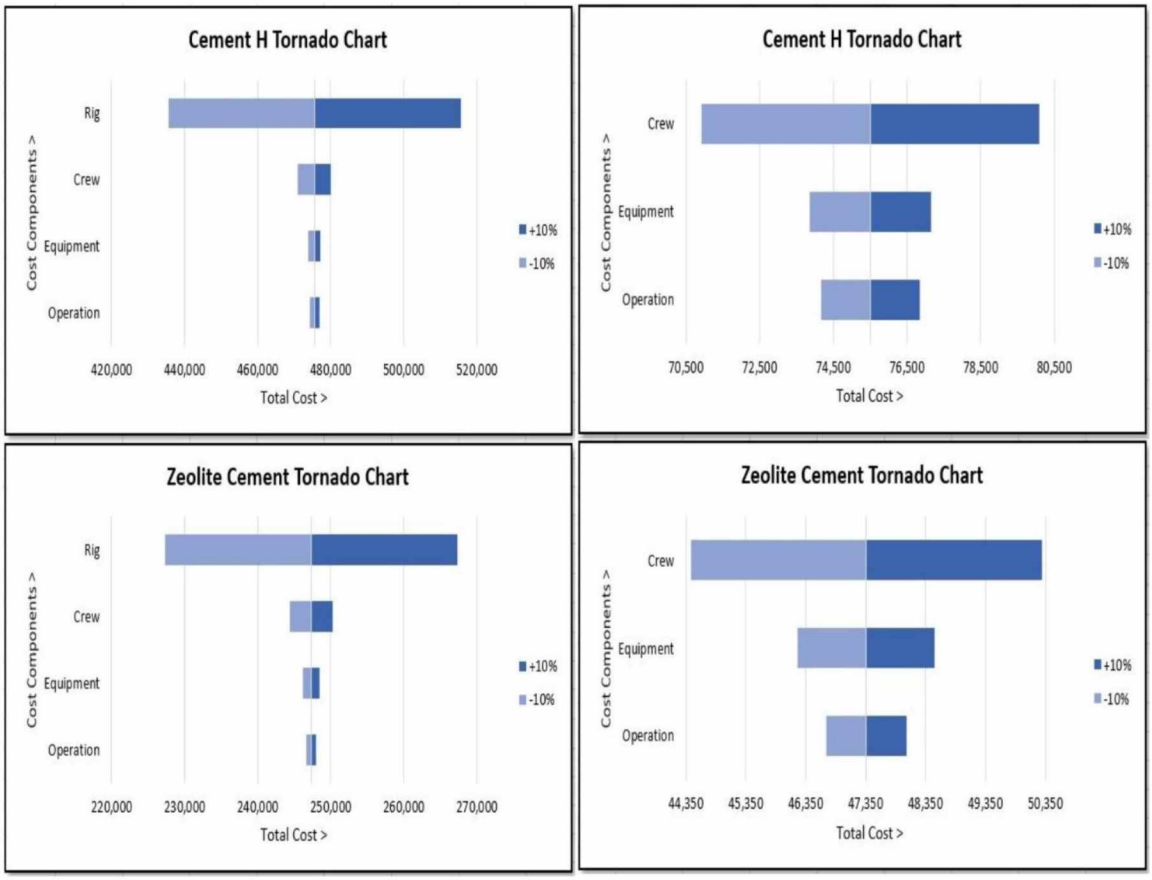

Figure 6.3: Case I Associated Costs Sensitivity Analysis

From Figure 6.3, we can safely conclude that the rig costs have the greatest impact on the overall associated cost. In this regard, rig costs are followed by the crew costs, equipment costs, and operation costs, in that order.

Cost Comparison

When only the cement costs are considered, the zeolite cement is by far the more expensive of the two options. The zeolite cement is approximately 14 USD/ft. more expensive than its class H cement counterpart for this example problem. However, once the associated

costs are considered in the total cost of the cementing operation, the zeolite cement is cheaper by approximately 62 USD/ft. than the class H cement for this problem.

Table 6.2: Case I Cost Comparison

Cement Volume Required		
Outer Diameter =	0.896	ft.
Inner Diameter =	0.723	ft.
Cement Rise behind Casing =	3000	ft.
Hole Volume =	659.520	cubic ft.
Fill - Up Factor =	1.5	
Cement Volume =	989.280	cubic ft.
Cement Cost		
Cost of Zeolite Cement =	46793.55	USD
Cost of Class H Cement =	4880.4	USD
Cost Difference =	-41913.2	USD
	-13.971	USD/ft.
Associated Cost		
Zeolite =	247570.6	USD
Class H =	475641.4	USD
Total Cost		
Zeolite =	294364.1	USD
Class H =	480521.8	USD
Cost Difference =	186157.7	USD
	62.053	USD/ft.

It is observed that using the zeolite cement in this example would provide savings of 186,157 USD. Therefore, it can be concluded that the lightweight zeolite cement blend is economically viable.

6.2 Case II: Low Temperature Geothermal Well Cementing

The example used in this case is the Pilgrim Hot Springs in Alaska. This case does not have the conditions under which the zeolite cement is expected to be used. Therefore, economic

viability here would prove the versatility of the zeolite cement. The Pilgrim Hot Springs project drilled a large number of holes, however, only a few of them were considered successful. From the ACEP "Pilgrim Hot Springs Geothermal Exploration 2012-2014 Final Report" (Alaska Center for Energy and Power (ACEP) and the University of Alaska at Fairbanks (UAF), 2010 - 2014), it was ascertained that the only hole of interest was the well classified as 'PS 12-1'.

Well Details

Only three wells fit the required temperature profile for geothermal energy production, of which only PS 12-1 did not require drilling through bedrock. This makes it favorable for geothermal energy production. Therefore, for the purposes of this case, it will be assumed that well 12-1 is cemented using the lightweight zeolite cement.

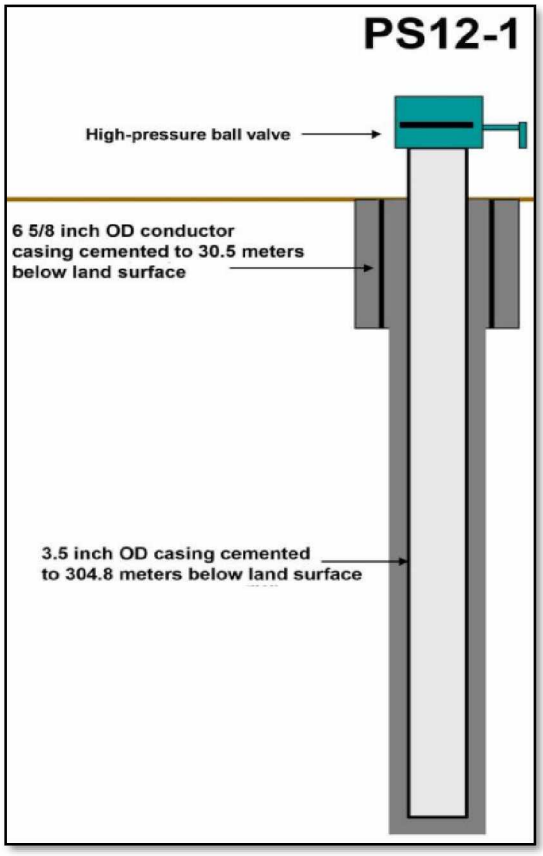

Figure 6.4: A Schematic Diagram of Well PS 12-1 (Alaska Center for Energy and Power (ACEP) and the University of Alaska at Fairbanks (UAF), 2010 - 2014)

In this well, we first have a hole of inner diameter $9\,^{7}/_{8}$ inches that has been completed with a conductor casing with an outer diameter of $6\,^{5}/_{8}$ inches. This extends to 30.5 meters (100.066 ft.) below the land surface. Therefore, the volume of the hole that has been cemented is 29.267 ft^3. Next, we have a hole of inner diameter 6 inches that has been completed with a Heavy Weight (HW) casing with an outer diameter of 3.5 inches. This extends to 304.8 meters (1000 ft.) below the land surface. Therefore, the volume of the hole that has been cemented is 129.536 ft^3.

Mode of Power Generation

Since the wells drilled at the Pilgrim Hot Springs were simply to study the feasibility of geothermal energy generation at this site, they were used to measure subsurface temperature changes. There are no active geothermal wells in this region producing energy. Judging by the geothermal energy generation setup employed at the Chena Hot Springs, it is reasonable to assume that similar facilities could be set up at the Pilgrim Hot Springs site. Chena employs a binary heat exchanger as part of its surface facility to generate energy.

Figure 6.5: Chena Hot Springs Binary Power Plant (Kagel, 2008)

In binary power plants, the geothermal well allows hot water, steam, or a combination of the two to travel to the surface, where they are passed into a heat exchanger. The heat exchanger contains another fluid, known as the working fluid (either isopentane or isobutane), that receives heat transferred from the water from the well. The working fluid is never exposed to the water. However, as the working fluid is chosen to have a lower boiling temperature compared to the water from the geothermal well, it vaporizes into gas. The force of the expanding gas then turns the turbines that in turn power the generators. Once the water passes through the heat exchanger it is then reinjected into the reservoir to keep emissions at or near zero, while at the same time maintaining the reservoir pressure, thereby extending the lifetime of the project. Therefore, a total of two wells need to be drilled for this project (Kagel, 2008).

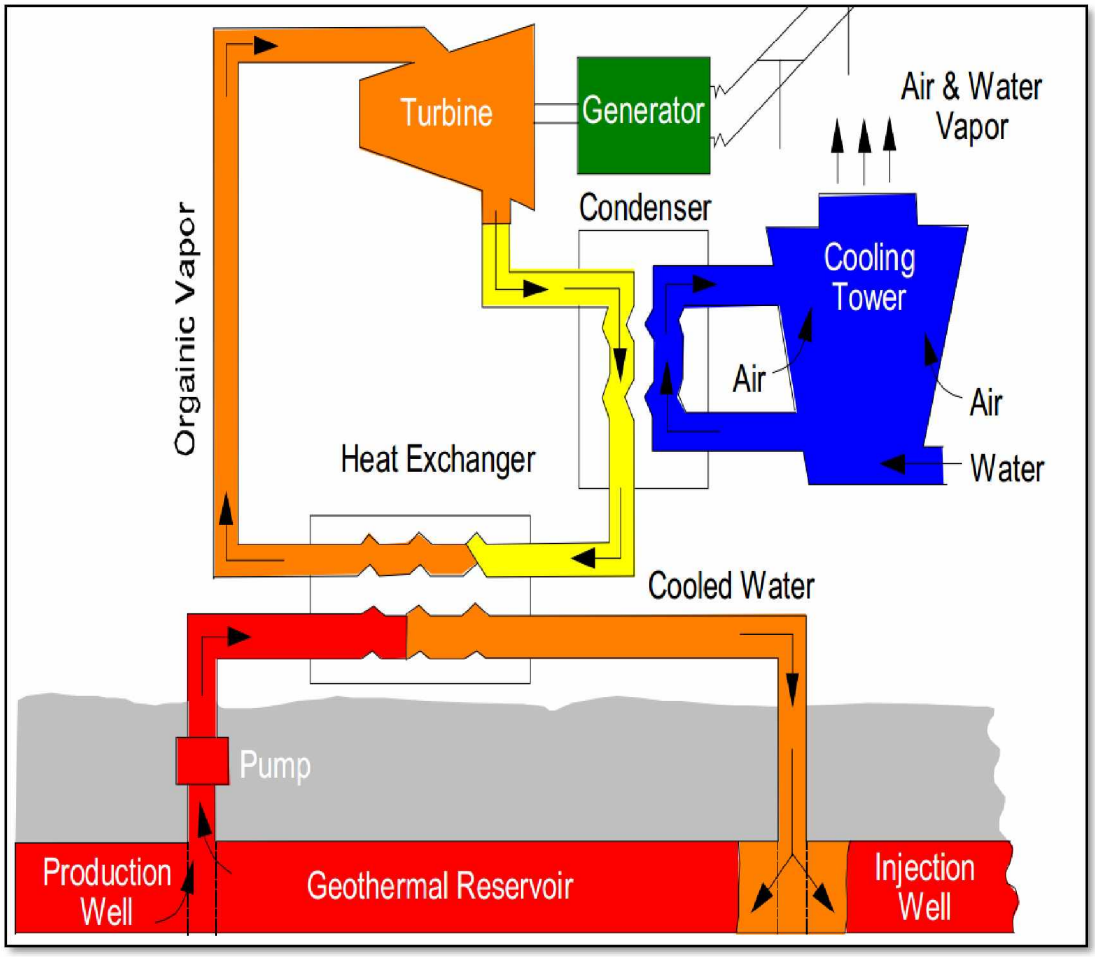

Figure 6.6: Schematic of a Binary Power Plant (Kagel, 2008)

Since Alaska is cold for a major portion of the year, the cooling tower is not required. The approximate summertime efficiency drop due to this omission can be as large as 15%. However, since winter performance is not affected, the cost savings and the drop in emissions makes this decision an economically viable one.

Associated Costs

For Class H cement, the Monte Carlo Simulation yields an associated cost of approximately 152,304 USD, as shown in Figure 6.7.

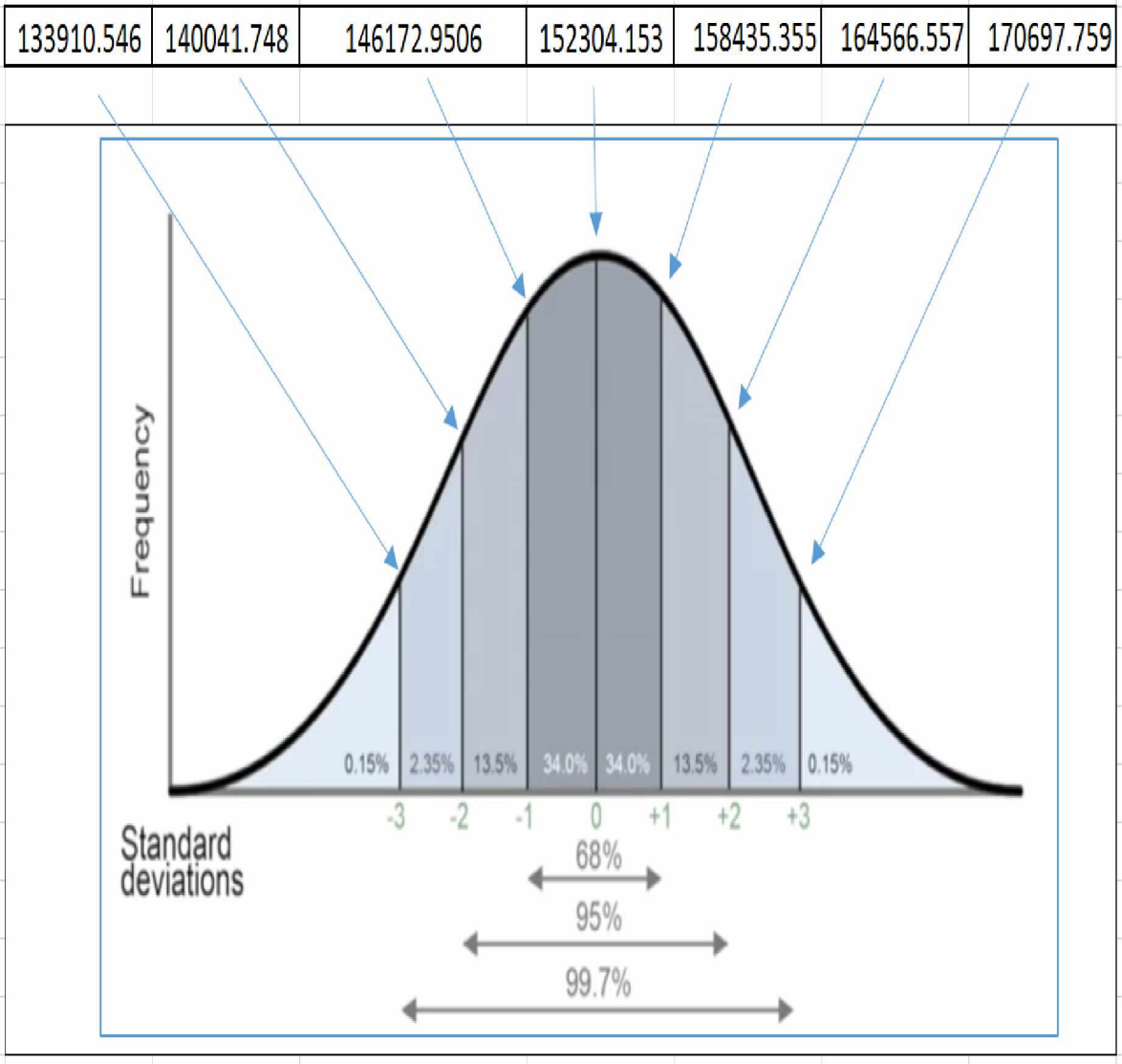

Figure 6.7: Monte Carlo Simulation for Case II Class H Cement Associated Costs

For lightweight zeolite cement, the Monte Carlo Simulation yields an associated cost of approximately 135,783 USD, as shown in Figure 6.8.

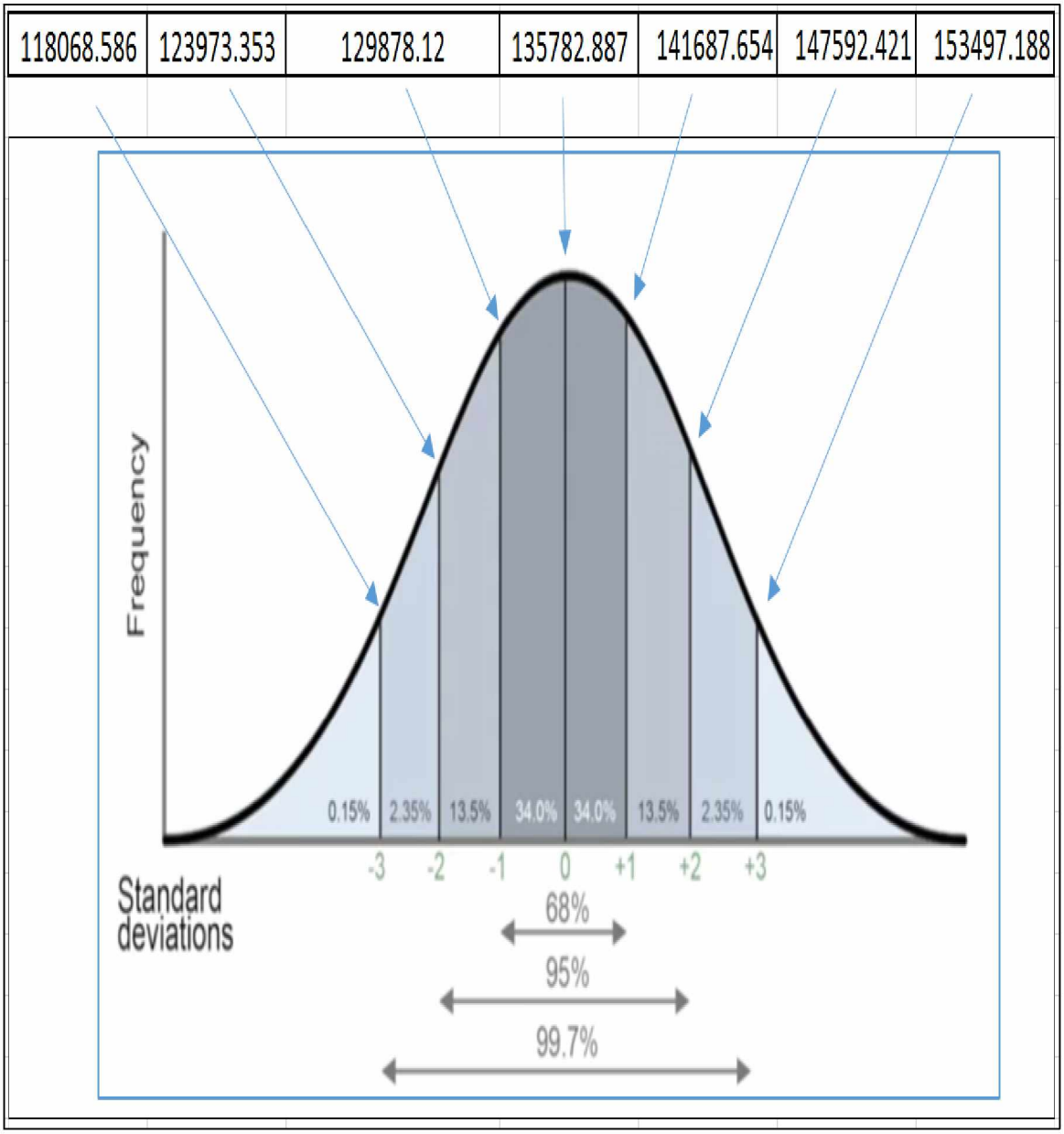

Figure 6.8: Monte Carlo Simulation for Case II Zeolite Cement Associated Costs

Cost Comparison

The costs for the two stages of cementing are calculated separately and then combined to arrive at the total cost of the cementing operation. Since the fill-up factor for the cementing job is taken to be 50%, the volume of cement required will be 1.5 times the volume of the hole to be cemented. Furthermore, the cementing job will not take more than a day to complete each time, so each component of the associated costs must be applied for only a single day (except the wages of the cementing crew, which are paid on an hourly basis).

Table 6.3: Case II Cost Comparison

Hole Diameter (inches)	9.875	6
Casing Diameter (inches)	6.625	3.5
Depth (meters)	30.5	304.8
Hole Radius (ft)	0.411	0.25
Casing Radius (ft)	0.276	0.146
Depth (ft)	100.066	1000
Volume (ft3)	29.267	129.536
Fill-up factor	1.5	1.5
Cement Volume Required (ft3)	43.901	194.304
Cost of Zeolite Cement	2076.528	9190.714
Cost of Class H Cement	216.574	958.559
Associated Costs (Zeolite Base)	135782.887	135782.887
Associated Costs (Class H Base)	152304.153	152304.153
Total Cost		
Zeolite Cement	282834	USD
Class H Cement	305784	USD
Cost Difference	22950	USD

From Table 6.3, we can see that the use of zeolite cement saves about 22,950 USD (about 21 USD/ft. for well 12-1) per well that is drilled. However, simply being a cheaper alternative than competing cements is not sufficient. Economic viability can only be claimed if the project has the capability of being profitable. The following section will attempt to conclude whether the geothermal project will be a financial success.

Total Project Cost

The typical cost of a geothermal energy project using binary power generation as specified by the International Energy Agency (IEA) is approximately 2400 to 5900 USD for every Kilowatt-Electric (KWe) produced by the project (International Energy Agency (IEA), 2010). According to the Office of Energy Efficiency and Renewable Energy (U.S Department of Energy (U.S - D.O.E), n.d.), the maintenance cost required to sustain the facility is about 0.01 to 0.03 USD per Kilowatt-Electric produced. Using these numbers, we can attempt to calculate the expected revenue of the geothermal project over a 30-year period, taken to be the life of the well (Sullivan et al., 2010) and the change in cost if the standard cement is replaced with a zeolite cement.

Table 6.4: Case II Total Project Cost

Appraisal of Pilgrim Hot Springs Geothermal Energy Generation				
Installed Capacity :	750	kWe		
Life of Well :	30	years		
Total kWhr produced :	197,226,000	kWe		
Rate charged :	0.045	USD/kWe		
Total Revenue :	8,875,170	USD		
Typical Geothermal project cost :	1,800,000	to	4,425,000	USD
Cementing Cost change :	-45,900	USD		
Zeolite Well Geothermal Project Cost :	1,754,100	to	4,379,100	USD
Operating and Maintenance Costs :	1,972,260	to	5,916,780	USD
Revenue with Standard Cement :	5,102,910	to	-1,466,610	USD
Revenue with Zeolite Cement :	5,148,810	to	-1,420,710	USD
Change in Revenue :	45,900	USD		
Pilgrim Hot Spring Well PS 12-1 total cemented depth =		335.3	meters	
	=	1100	ft.	
Therefore, using zeolite cements,				
Cost per kWhr :	0.019	to	0.052	USD

By looking at the calculation, we can see that using the zeolite cement can save approximately 45,900 USD. Depending on the cost of the geothermal project itself, the worst-case scenario indicates a loss of 1,420,710 USD and the best-case scenario indicates a profit of 5,148,810 USD when the lightweight zeolite cement blend is used. The cost of electricity generation ranges from 0.02 to 0.05 USD/Kilowatt-hour (kWhr). Therefore, it is reasonable to expect the project to be economically viable for a certain range of project costs.

6.3 Case III: Standard Temperature Geothermal Well Cementing

It is uncommon to have a geothermal well operating at about 98°C. Most geothermal wells actually operate closer to 165°C, with some of the highest ones operating at over 280°C. The high temperature resources are quite rare, so in this section we will look at a fairly typical geothermal project. The temperatures can be expected to be between 165°C and 182°C (i.e. 330°F to 360°F) and are therefore prime for employing a flash geothermal power plant. The examples used in this case are the PGM-1 wells in the Miravalles project developed in a Costa Rican geothermal resource (Kim, 2000). This case contains the conditions under which the zeolite cement is expected to be used.

Well Details

The PGM-1 wells in the Miravalles project comprise of 8 production wells and 6 reinjection wells. These wells are cemented to a depth of 852 meters (approximately 2795 ft.) with three sections. The first cemented section is to a depth of 174 ft from the surface and inner and outer radii of 0.83 ft and 1.083 ft, respectively. The second cemented section runs from the surface to a depth of 997 ft and has inner and outer radii of 0.557 ft and 0.724 ft, respectively. The last cemented section runs from the surface to a depth of 2795 ft and has inner and outer radii of 0.4 ft and 0.51 ft, respectively.

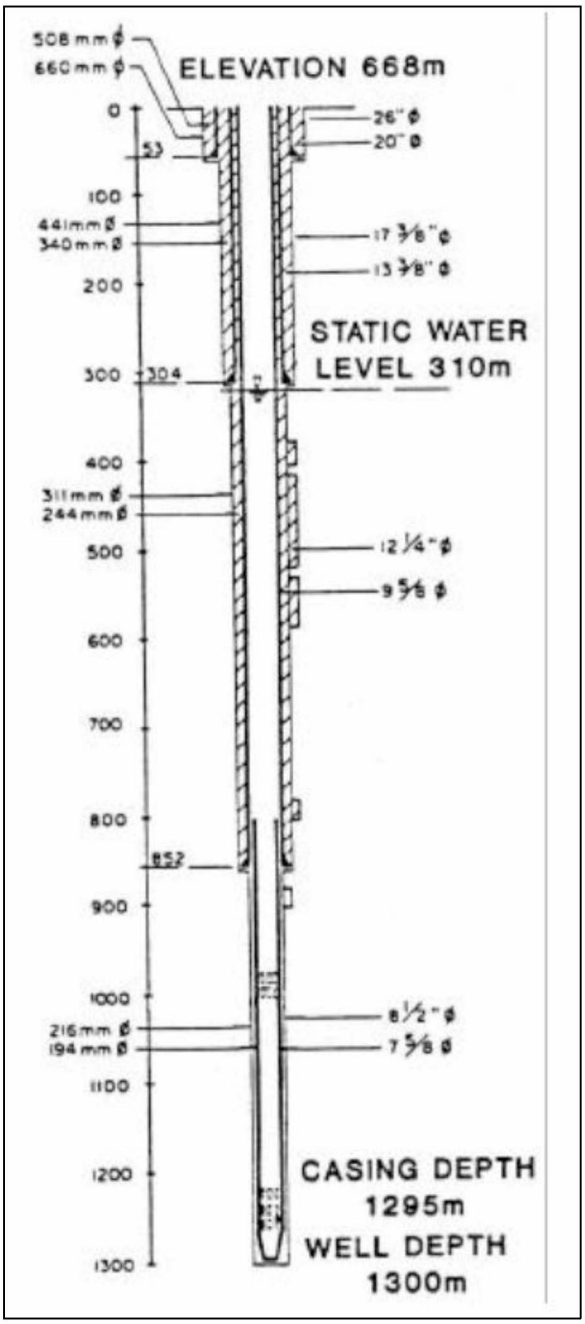

Figure 6.9: A Schematic Diagram of a PGM-1 Well (Kim, 2000)

Therefore, the volume of the hole to be cemented is 1806 ft^3 and the cement volume required, considering the fill-up factor, is 2709.5 ft^3.

Mode of Power Generation

The Miravalles project employs the use of a flash geothermal power plant to produce electricity. This type of power plant is used for a large number of geothermal projects as it can operate over a large range of temperatures, particularly of the range within which most geothermal resources are found. In a flash geothermal power plant, water is present within the reservoir at a high temperature but is not boiling due to the high pressure. As the reservoir fluid is produced and brought to the surface, the pressure drop causes it to flash to steam. This steam is then used to power the turbine of the generator. The remaining hot water can then be used as a direct heat source using heat exchangers and/or pumped back into the reservoir by means of an injection well to maintain the reservoir pressure for a longer period. Furthermore, multiple flash stages can be utilized to capture more of the heat of the reservoir fluid being brought to the surface. However, this also results in concentration of the other chemical components (minerals and other impurities) that may be present in the reservoir water.

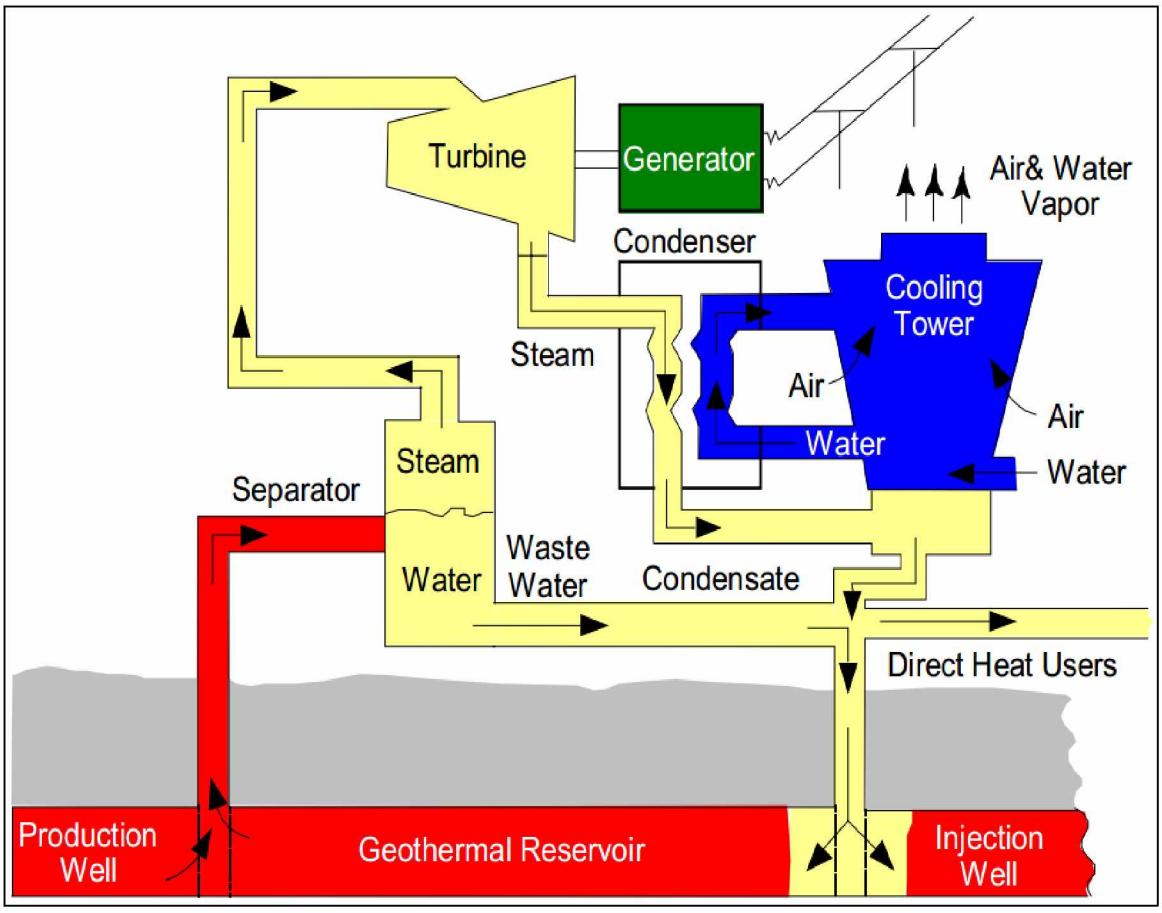

Figure 6.10: Single Flash Steam Power Plant Schematic Diagram (Kagel, 2008)

In the PGM-1 wells, the temperature range within which the cement utilized is approximately 125°C to 200°C (i.e., 257°F to 392°F). This is within the safe operational range of the Fmix1 zeolite cement blend.

Associated Costs

The first two sections of cementing will have similar associated costs. However, they will differ from the associated costs of cementing the third section, as the time required to carry out the cementing of the third section is significantly higher. For class H cement, the Monte Carlo method yields an associated cost of 152,328 USD for the first two sections and an associated cost of 155,927 USD for the final section. For the lightweight zeolite cement blend, the Monte Carlo method yields an associated cost of 135,995 USD for the first two sections and an associated cost of 139,585 USD for the final section.

Cost Comparison

Since we already know the amount of cement required to cement the well properly, we can calculate the overall cost of cementing the well once we take into account both the cement and associated costs associated with a particular type of cement. In this case, the zeolite cement will cost 65,785 USD more per well compared to the cost of using class H cement.

Table 6.5: Case III Cost Comparison

Outer Diameter (inches)	26	17.375	12.25
Inner Diameter (inches)	20	13.375	9.625
Depth (meters)	53	304	852
Outer Radius (ft.)	1.083	0.724	0.510
Inner Radius (ft.)	0.833	0.557	0.401
Depth (ft.)	173.884	997.375	2795.276
Volume (ft^3)	261.756	669.100	875.446
Fill-up factor	1.5	1.5	1.5
Cement Volume Required (ft^3)	392.635	1003.650	1313.169
Cost of Zeolite Cement	18571.870	47473.295	62113.735
Cost of Class H Cement	1936.980	4951.295	6478.240
Associated Costs (Zeolite Base)	135995	135995	139585
Associated Costs (Class H Base)	152327.5	152327.5	155927
Total Cost			
Zeolite Cement	539734	USD	
Class H Cement	473949	USD	
Cost Difference	65785	USD	

Table 6.5 can now be used to study the expected revenue from the 55 MWe (Megawatt-Electric) power plant constructed by Toshiba to generate electricity from this geothermal resource.

Total Project Cost

The typical cost of a geothermal energy project using binary power generation as specified by the International Energy Agency (IEA) is approximately 2000 to 4500 USD for every Kilowatt-Electric (KWe) produced by the project. According to the U.S Department of Energy (U.S D.O.E), the maintenance cost required to sustain the facility is about 0.01 to 0.03 USD per Kilowatt-Electric produced. Using these values, we can attempt to calculate the expected revenue of the geothermal project over a 30-year period, taken to be the life

of the well (Sullivan, Clark, Han, & Wang, 2010), and the change in cost if the standard cement is replaced with a zeolite cement.

Table 6.6: Case III Total Project Cost

Appraisal of PGM - 1 Geothermal Energy Generation				
Installed Capacity :	55,000	kWe	(= 55MWe)	
Life of Well :	30	years		
Total KWhr produced :	14,463,240,000	kWe		
Rate charged :	0.045	USD/kWe		
Total Revenue :	650,845,800	USD		
Typical Geothermal project cost :	1.1E+08	to	2.48E+08	USD
Cementing Cost change :	920,990	USD		
Zeolite Well Geothermal Project Cost :	110,920,990	to	2.48E+08	USD
Operating and Maintenance Costs :	144,632,400	to	4.34E+08	USD
Revenue with Standard Cement :	396,213,400	to	-3.1E+07	USD
Revenue with Zeolite Cement :	395,292,410	to	-3.1E+07	USD
Change in Revenue :	-920,990	USD		
PGM - 1 total cemented depth =		1209	meters	
	=	3967	ft.	
Therefore, using zeolite cements,				
Cost per kWhr :	0.018	to	0.047	USD

By looking at the calculation, we can see that using the zeolite cement will cost approximately 920,990 USD more than using the class H cement for all the wells together. Depending on the cost of the geothermal project itself, the worst-case scenario indicates a loss of 31 million USD and the best-case scenario indicates a profit of 395 million USD when the lightweight zeolite cement blend is used over the course of the 30-year life of the wells. The cost of electricity generation ranges between 0.02 and 0.05 USD/Kilowatt-hour (kWhr).

An important point to be noted is that the use of standard class H cement is very likely to cause well failure in this example, given that the temperatures are around 350°F and the class H cement is not using any system of additives to help it cope with the HTHP conditions. In such an eventuality, extra costs will be incurred due to the loss in power generation resulting from the shutdown of the well and the expense of well remediation. The lightweight zeolite cement is unlikely to face such problems. Therefore, in the end, the use of zeolite cement may still be more economical, as the cost of well remediation can easily exceed the price difference between the two different cements.

Therefore, it is reasonable to expect the project to be economically viable for a certain range of project costs using zeolite cements, the safer alternative out of the cement choices.

6.4 Comparisons between different sources of Electric Power Generation

Whether or not Fmix1 is a viable candidate for use in geothermal wells becomes a moot point if geothermal energy itself is not an attractive choice out of the multitude of different renewable energy sources available. Therefore, a comparison between different sources of electric power generation is important in demystifying the candidature of geothermal energy as the focus of renewable energy research.

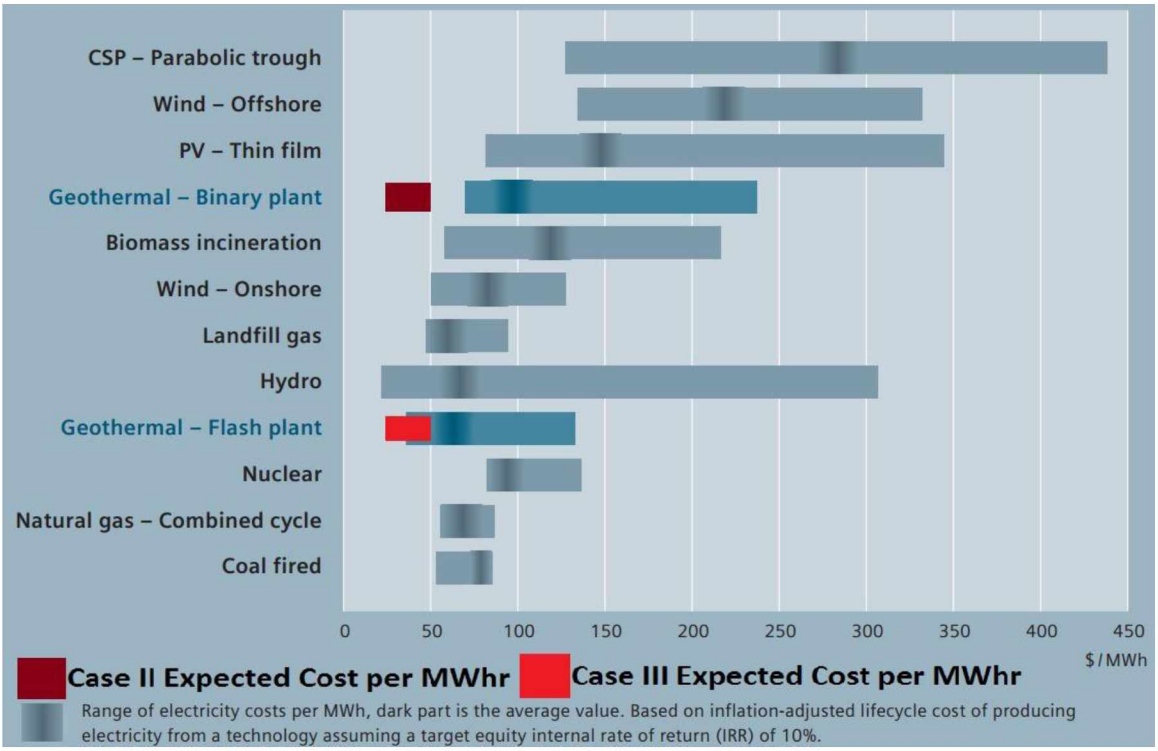

Figure 6.11: Leveled Costs of Energy across a variety of different Power Generation Technologies (Siemens, 2012)

According to a study conducted by Siemens, we can see that the cost of electricity generation per MWhr is comparable for geothermal power plants (~80 USD/MWhr), hydroelectric power plants (~70 USD/MWhr), and coal-fired power plants (~80 USD/MWhr). In fact, flash type geothermal power plants (~65 USD/MWhr) outperform both coal and hydroelectric power plants (Siemens, 2012). Therefore, we see that geothermal sources of energy are not only financially viable among renewable sources of energy, but also an attractive option when compared to hydrocarbon sources that are nonrenewable and historically profitable.

The costs calculated in the case studies were found to be lower than those in the Siemens study were. This is likely due to the lower crew costs estimation carried out in the case studies. In addition, costs such as well insurance premiums were not directly accounted for. Changing the type of cement can be expected to have an impact on this. Therefore, the availability of more data, especially more real – world data, would help improve the cost estimation as shown in the case studies.

7. Conclusions and Recommendations

Based on the studies conducted, the following conclusions can be drawn:

- A 40% replacement of ferrierite by weight of cement shows the best properties for a lightweight HTHP cement that fulfills the requirements set forth by the American Petroleum Institute (API).
- A blend of additives is required to ensure that the zeolite cement blend consistently performs at API standards.
- The cement cost of the zeolite cement blend is higher than that of just class H cement. However, the associated cost is lower.
- The zeolite cement blend is cheaper for jobs requiring comparatively smaller quantities of cement. However, when larger quantities of cement are involved, the savings obtained from the associated cost can no longer outweigh the higher cement cost of the zeolite cement blend.
- In certain cases, class H cement may be the cheaper option in initial cementing, but might not be the safer option. Zeolite cement blends, by the virtue of their properties, will have a much lower chance of causing well failure.
- Geothermal energy can be a profitable business. In particular, the use of zeolite cement blends can help reduce the costs associated with establishing and maintaining a geothermal energy project, thereby increasing the revenue obtained from it.

Some recommendations for future work are:

- Finding the exact probability of well failure when using Class H cement and the zeolite cement blend under a certain set of HTHP conditions.
- Factoring in the cost of remediation and the higher well insurance payments required after a Class H cement well fails, to see if the zeolite cement blend is more profitable to use if it does not cause well failure under similar conditions.
- Developing new blends that rely on different proportions of strength additives. Less diatomaceous earth and more microsilica would allow for the development of cements with extremely low porosity and permeability. This is because diatomaceous earth is the fossilized remains of diatoms such as phytoplankton and porous by its very nature. Using a microsilica such as Unimin's SilverBond Ground Crystalline Silica (Unimin Corporation) should be interesting.
- Mixing two different types of zeolites in a single zeolite cement blend to see if it has better HTHP performance than Fmix1.
- Studying the effect of corrosive substances brought up with formation water in geothermal wells on the Fmix1 zeolite cement blend.

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